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AN EVALUATION OF SIDE LOOKING RADAR IMAGERY OF SEA ICE FEATURES AND CONDITIONS IN THE LINCOLN SEA, NARES STRAIT, AND BAFFIN BAY (U)

R. D. KETCHUM JR.

Oceanography Division
Naval Oceanographic Laboratory

April 1977

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NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
NSTL Station, Mississippi 39529

FOREWORD

Evaluation of remote sensor sea ice data interpretation capabilities is a continuing goal of the NORDA Polar Oceanography Branch so that new/improved techniques and methodology can be considered for application to arctic environmental studies which are conducted in support of ASW and ice forecasting objectives. The radar imagery evaluated for this report was collected to determine the capabilities of a state-of-the-art side looking radar system to provide information concerning sea ice features and conditions. The results of this evaluation have been revealing and encouraging. Hypotheses explaining radar backscatter have opened new avenues for sea ice research. This system or a similar system properly used could provide a powerful tool in sea ice research studies and in operational applications.

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Evaluation of synthetic aperture radar sea ice imagery has shown that discrimination of first season ice types can be difficult due to ambiguous radar returns. It has been hypothesized that varying balances of ice thickness, snow depth, air temperature, and time will produce conditions at the snow-ice interface which are conducive to the development of radar reflective surfaces with variable backscatter characteristics. The presence of this phenomenon was common in Baffin Bay where climatic conditions fluctuate widely. This phenomenon should be anticipated in other

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areas of the marginal ice zone.

Multi-year ice forms were easy features to identify. Generally uniform returns from multi-year ice are believed to be due to volume scattering. Many of the larger frozen melt ponds on multi-year ice were identifiable. It is hypothesized that the radar energy penetrates the fresh water ice which comprises these ponds and is attenuated in the underlying multi-year ice. High returns seen within some of these ponds are believed to come from areas where thaw holes formed during the previous melt season. The question of the penetrability of large vertical sections of multi-year ice, particularly by longer wavelengths, is raised. This question deserves serious consideration because of the possible implication on air to submarine communication.

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EXECUTIVE SUMMARY

This report describes the results of a synthetic aperture side looking radar (SLR) experiment to evaluate x-band imagery of sea ice features and conditions over areas of the Lincoln Sea, Nares Strait, and Baffin Bay. The SLR data were collected on 7 May 1975. The Naval Oceanographic Office Project BIRDSEYE P-3A aircraft, during the period 1-11 May operating from Thule AB, Greenland, collected photographic and thermal infrared imagery over large portions of the same sea ice terrain for comparison with the SLR imagery.

With some reservations, the ability to interpret sea ice features and evaluate sea ice conditions was generally very good in the more northerly arctic areas of Nares Strait and the Lincoln Sea. Interpretation and discrimination of the more dominant young stages of ice development and pressure ridges found in Baffin Bay were much more difficult due to an anomolously high homogeneous radar return associated with some ice conditions in this area. This has been attributed to climatic conditions.

Multi-year ice forms were easy targets to discriminate because of their shapes and somewhat predictable backscatter characteristics. Younger stages of ice development can be easily discriminated from the older, thicker multi-year ice, but often these forms cannot be discriminated from each other based on backscatter information and pattern analysis.

Fractures within the ice field were usually identifiable because of their characteristic shapes, however the stage of ice development (or water) which covers a fracture cannot always be identified.

It has been shown that radar backscatter alone is not always a sufficient criterion for identifying or classifying stages of ice development. This was found to be particularly true in the Baffin Bay environs and this truth can be extrapolated to include other areas within the marginal ice zone. It is important that this be understood since some investigators in the past have tried to use this single criterion for classifying sea ice types.

New ice ridges and hummocks usually provided a good radar return. This, combined with their linear character make them easily identifiable targets when the adjacent background radar backscatter is comparatively low. Old weathered ridges and hummocks usually provide a radar backscatter similar to their multi-year ice backgrounds, hence they usually remain obscure. This fact lends credence to the speculation that radar returns from multi-year ice are largely due to volume scattering.

The high quality engineering parameters of this radar system enabled identification of many frozen melt ponds on multi-year ice floes. These areas provide a low radar return. It has been hypothesized that the radar energy penetrates the relatively fresh water ice which comprises frozen melt ponds and is attenuated in the underlying multi-year ice. Bright returns seen within the dark area of some of these ponds are believed to represent reflections from thaw holes (where ponds melt through to the underlying sea water during the summer). The bright return is attributed to a strong reflection at the fresh ice/new sea ice interface.

This analysis has revealed that under certain conditions snow cover may play an important role in the development of a strongly radar reflective layer at the snow-ice interface. It has been speculated

that proper balances of ice thickness, snow depth (and density), air temperature, and time will enhance conditions at the snow-ice interface which are conducive to the formation of a high dielectric, radar rough layer which provides a high radar backscatter.

There is a need for surface truth observations to confirm and answer many of the hypotheses and questions forwarded in this evaluation. The formulation of hypotheses which attempt to explain radar backscatter characteristics has revealed new avenues for research in the sea ice environment. Particular reference is made to electromagnetic windows in the sea ice cover in the form of frozen melt ponds. But in addition to these specific features, the possibility of electromagnetic transmissions through a large portion of the vertical sections of old multi-year floes cannot be overlooked. It appears evident that volume scattering and/or some subsurface layers provide the primary reflective zones. The upper portions of old multi-year ice floes have experienced much reconstituion. Salts have been drained and/or leached from the ice and much of this material has been replaced with fresh water during the melting seasons. The result may be that a large portion of this reconstituted ice is at least partially transparent to electromagnetic energy, particularly the longer wavelengths. If this is true, air to submarine communication through sea ice may be made possible by penetrating an antenna through the lower, high conductivity layer of sea ice which acts as a shield to electromagnetic energy, and receive (or transmit) through the upper, more transparent layers. Field experiments could reveal the feasibility of this technique.

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AN EVALUATION OF SIDE LOOKING RADAR IMAGERY OF SEA ICE FEATURES AND CONDITIONS IN THE LINCOLN SEA, NARES STRAIT, AND BAFFIN BAY

I. INTRODUCTION

The potential use of side looking radar (SLR) in sea ice research and operational programs has been recognized for many years. Results from past SLR sea ice programs which have utilized the various radar frequencies have indicated that x-band and k-band radar systems are the most useful for sea ice reconnaissance and mapping. These shorter wavelength systems are much more sensitive to ice properties, so they can be used to portray a wider variety of sea ice features than the longer wavelength radar systems. It can be argued that the shorter wavelengths are vulnerable to absorption and attenuation when atmosphere water volume is high. However, since this condition is uncommon in most areas of the polar regions, it should not be used as a criterion in selecting a SLR frequency for sea ice reconnaissance and mapping. Aside from the near all weather, day-night, broad area coverage capabilities, the present synthetic aperture systems provide imagery with good surface feature resolution and low geometric distortion. SLR is the only remote sensing system which offers all these advantageous features.

This paper presents an interpretive analysis with discussion of synthetic aperture x-band SLR imagery obtained on 7 May 1975 along tracks traversing Baffin Bay, Nares Strait, and the Lincoln Sea. The areas of SLR coverage are shown in Figure 1. These areas were selected because they possess characteristically different ice conditions, thus enabling a more comprehensive analysis. In addition, since ice conditions in Kane Basin and northward through the Lincoln Sea are generally static in May it was reasonable to assume that correlative airborne data collected before and after the SLR aircraft flight would be valid for use in interpretation of the SLR imagery. The more ephemeral ice conditions in Baffin Bay required near coincident data collection. The Naval Oceanographic Office (NAVOCEANO) Project BIRDSEYE P-3A aircraft, operating from Thule AB, Greenland, during the period 1-11 May, was tasked to collect documentary data for cross correlation with the SLR imagery. This plan allowed sufficient time to obtain a significant amount of documentary data for correlation and reduced the effects that periods of adverse weather could have on mission success.

In the following presentation a comprehensive review is given to interpretive results including the development of hypotheses which attempt to explain some anomalous or unanticipated images. An assessment of general ice conditions in each of the three physiographically different areas is given.

II. DATA FORMS AND QUALITY

The SLR data were collected over the areas shown in Figure 1 from opposite sides during northward and southward flights. During flight, data were recorded on two channels (A and B). Each channel represented a surface swath width of slightly over 2.5 nmi. There is a small side lap of channels so that total swath coverage equals 5 nmi. The optically processed data were displayed on 70mm film. Channel A consistently gave poor results with respect to a uniform field. However, since the same area was viewed from opposite sides during the northward and southward flights, the total area has been covered by Channel B. No significant difference in sea ice feature portayal has been noted due to viewing from opposite sides. Apart from the substandard results obtained on Channel A, the data were of high quality, possessing good dynamic range and surface resolution.

Correlative data, which were collected by the NAVOCEANO BIRDSEYE aircraft, included 9-inch frame cartographic photography, infrared scanner imagery, and laser surface profile data. The quality of the photography, which was usually obtained from altitudes of 4000 to 6000 feet was fair to good. Some photography was lost due to a period of camera malfunction. The infrared scanner imagery is considered fair to poor in quality and did not add much to the interpretational analysis. The laser surface profile data were not used in this analysis. The BIRDSEYE aircraft photography served as the major supportive reference in interpretative analysis of the SLR imagery.

III. RESULTS

A. General

Radar surface backscatter is dependent on a number of system and environmental parameters. Primary system parameters which influence radar backscatter are transmitter power, antenna angle, frequency, and polarization. These parameters remained constant during this experiment with the exception of antenna angle which had to be changed slightly along with minor altitude changes in order to maintain a constant near range of 10 nautical miles. The differences in feature portrayal on imagery taken during this experiment are primarily due to environmental parameters such as topography (which affects the angle of incidence of the radar energy), surface roughness (as it relates to the radar wavelength), and feature dielectric properties. Topographic features can be seen on comparative photography, thus are easily related to the radar image, but surface roughness, as related to radar wavelength, and surface dielectric properties cannot be determined from comparative photography. Since no ground truth data was available for documentation of these parameters, hypotheses based on available knowledge and experience have been developed and presented to explain certain radar backscatter phenomena.

B. Preliminary Analysis

When assessing sea ice conditions there are a number of basic parameters which are taken into account. They include (1) ice edge, (2) ice concentration, (3) stages of ice development, (4) ice forms, (5) topography, (6) fractures and/or water openings, (7) snow cover, and (8) ice melt or pools and puddles. The importance of each of these parameters depends on the user's application. For most operational and research applications parameters (1) - (6) have been considered most important.

Initially, the SLR imagery was examined without aid from other data sources. The general ice conditions portrayed on the SLR imagery representing sections of Nares Strait and the Lincoln Sea were interpreted with considerable confidence. This was possible because of previous experience in analyzing SLR sea ice imagery backed by general knowledge of existing ice conditions based on visual observation during the mission and historical information. However, there are some areas and targets where interpretations were highly questionable. In subsequent analysis, using correlative photography and IR scanner imagery, when available, interpretations of some features often remained extremely subjective.

The Baffin Bay imagery was by far the most complex and difficult to interpret. Although the analyst is aware that the area is comprised primarily of first-year ice and younger stages of ice development with scattered multi-year ice floes, icebergs, and water openings, their discrimination is often very difficult. Much of the area of first-year ice and younger ice types gave a

non-characteristic high radar backscatter. It is hypothesized that climatic conditions in Baffin Bay are largely responsible for the development of surface conditions conducive to the backscatter of x-band radar. This is further expounded in Section III C.

C. Radar Backscatter vs. Environmental Features

It became evident during the analysis that together, snow depth and ice thickness may play a far more important role in radar image portrayal than has been recognized in previous similar investigations. It is hypothesized that the relative quantity of these parameters, snow depth and ice thickness, can strongly influence the development of a radar reflective surface at the snow-ice interface. To amplify, the development of this radar backscatter surface is generated by the accumulation of heat from below at the snow-ice interface. The increased amount of heat produces two basic phenomena. Salt or brine within the ice migrates to this warmer zone increasing the salinity, thereby increasing the dielectric constant. Sufficiently high temperatures in this zone, due to the accumulated heat, cause metamorphosis of the ice and snow at their boundary and development of a recrystallized zone which is rough to the x-band radar energy. The resulting combination of a radar rough surface and increased dielectric constant produces a good radar backscattering surface. The amount of heat which accumulates at the snow-ice interface is primarily a function of ice thickness and depth and density of the snow cover, air temperatures, and time. Accepting the above postulation, it follows that areas of relatively thin ice with a deep snow cover would develop a very effective radar backscatter surface if these conditions persisted for a sufficient time. During summer seasons this radar backscatter zone will be largely reduced or eliminated by melt and water runoff conditions. Consequently, similar ice areas may appear completely different when using the same radar system in different seasons.

Radar image portrayal of sea ice conditions in Baffin Bay were the most variable and complex of the areas analyzed during this experiment. A number of reasons for this are suggested. The area is predominantly covered with various thicknesses of first-year ice and younger, thinner ice types. Minor changes or differences in the thickness of relatively thin ice have a pronounced effect on heat transfer through the ice. The brine content of these early stages of ice development is higher than in older ice. When these unstable conditions are subjected to the variable parameters of snow cover, air temperature, and time, the physical processes which result could conceivably produce any number of radar backscatter surfaces. The physiographic conditions of Baffin Bay, particularly climatic fluctuations during springtime, play an important role in these processes. In any event, it is believed that a very complex interrelationship of environmental features and processes are responsible for the production of a very complex radar reflective surface in Baffin Bay. Moreover, these results can probably be extrapolated for use in interpretation of x-band radar sea ice imagery in the Bering Sea and to some degree in the Greenland Sea.

D. Imagery Interpretations and Ice Assessments

1. Lincoln Sea Imagery

During the winter season, multi-year ice is generally displayed in rather homogeneous intermediate gray tones on x-band radar imagery as shown in Figure 2. The many old, weathered, smoothed over hummocks and ridges seen on the visual image densely scattered over the multi-year ice generally do not give a radar backscatter appreciably different from their background.

Hence, these features are not readily identifiable. Ridge age and/or orientation appear to be dominating factors which influence the degree of radar backscatter. Ridges displaying the brightest returns, such as those at A, are usually relatively new, comprised of blocky ice formations, and/or are more obliquely oriented with respect to the aircraft track. The highest ridges or ridge remnants in this scene, located at B are not well defined or easily distinguishable on the radar imagery. These are old, well weathered ridges and their longitudinal axes are oriented nearly parallel to the radar look angle.

The small first-year ice-covered fractures at C in the multi-year ice are more easily delineated on the SLR image than the visual image because of their contrasting dark gray tone which represents low or no radar backscatter. The dark tone could be indicative of first-year ice or younger ice types as well as open water.

The dark toned area in Figure 2, at D, with a bright radar return in the central portion is interpreted as a large frozen melt pond. Melt ponds or pools on multi-year ice contain water produced by summer melt of the snow and ice. This water, essentially salt free, freezes producing fresh water ice which is generally transparent to x-band radar energy. It is hypothesized that the dark area around the bright spot represents the area where the pond has frozen completely to the bottom coming into contact with multi-year ice. Radar energy passing through the fresh water ice is largely attenuated in the underlying multi-year ice layer. It is speculated that the bright spot represents a thaw hole which has been replaced with sea ice. A rough interface and a sharp dielectric boundary between the fresh water ice and underlying new sea ice formation in the thaw hole produced a high radar backscatter. Quite a few targets similar to this have been noted on the radar imagery during this analysis and in every case where comparative photography is available the area appears to be a large smooth area which is representative of frozen melt pools. Looking closely at the radar imagery of the multi-year ice, many small dark rounded areas are noted. These probably represent frozen melt pools.

Figure 3 shows an area in the Lincoln Sea covered with first-year and multi-year ice. The multi-year ice floes, some indicated by A, are easily distinguished from the first-year ice by their lighter gray tones and shapes. In some cases the smaller multi-year ice floes give a very bright return. The fairly dense network of new ice pressure ridges on the first-year ice indicates that this is relatively old thick first-year ice. The new ice pressure ridges which are composed of many fragments of broken ice, act as multiple corner radar reflectors and appear as light gray lineations on the dark first-year ice background of the SLR imagery.

The combination of shape and light gray tone make multi-year ice floes easily identifable targets on x-band radar imagery. In the Lincoln Sea scene shown in Figure 4, the many rounded multi-year floes of varying size are easily and accurately delineated and distinguished from the first-year ice. These are more difficult to delineate on the photography partially due to the masking effect of snow cover. The small size and rather rounded shape of the floes indicate that a great deal of floe interaction accompanied by rotational as well as translational motion has taken place in this field of ice. The degree of deformation is further attested to by the numerous hummocks, ridges, and broken fragments of multi-year ice contained in the first-year ice matrix. Note that these strongly deformed areas within the first-year ice, such as that at A, are portrayed in a fairly uniform light gray tone and texture. It is believed that wind transported snow, deposited in these areas of relatively high topographic relief, is responsible for phenomena which lead to development of a high radar backscatter surface at the snow-ice interface as discussed in Section IIIC. The radar

return seen in these areas is a combination of returns from the ridges and hummocks (visible on the photography) and from a radar reflective snow-ice interface. Note that the areas of generally level first-year ice possessing little snow cover are portrayed as very dark toned images.

The open fracture at B shown on the Figure 4 photography, which was taken two days prior to the radar imagery, cannot be definitely identified on the radar imagery. However, a narrow gray sinuous lineation is evident along this path on the radar image at B indicating deformational action in this zone.

Figure 5 shows a section of a vast multi-year ice floe in the Lincoln Sea which has undergone severe deformational stresses. This is evidenced by the many new ice ridges interlacing the entire floe. The ridges appear as light gray lineations on the radar image. This floe may eventually separate into many smaller individual floes. The ice rubble zone at A bordering the left side of the floe further attests to the severity of deformational forces here. This area of rubble is comprised of many fragments of multi-year ice and younger ice types frozen in a matrix of first-year ice. The rather high and homogeneous radar return from this zone is attributed primarily to the affects of deep snow which has been deposited by winds in this zone. As before, the masking effect of snow cover precludes easy separation of first-year and multi-year ice on the photography, but the radar sees through the snow enabling easier discrimination.

Figure 6 shows a 40-mile section of radar imagery with comparative infrared scanner imagery (negative prints) taken over the Lincoln Sea. The common area of the two strips is delineated on the radar and cross correlations of some of the same features are made to guide further comparison. On the infrared imagery warmer surface areas, such as areas of first-year ice, appear in a darker gray tone and the cooler surface areas, such as the multi-year ice appear in light gray tones. In comparing the infrared scanner imagery with the radar imagery it is immediately apparent that the major ice types are much more quickly and accurately identified on the radar imagery. This is largely due to the thermal masking effect the snow cover has on the IR imagery. The boundaries between first-year ice and multi-year are often poorly delineated on the IR imagery and some areas of first-year ice are completely obscured by snow. The new ice pressure ridges are also better delineated and more identifiable on the radar imagery, but the old ridges and hummocks which may go undetected on the radar are better defined on the IR imagery. An example of this is shown at A which is also shown on the photograph in Figure 2 at B. Solar radiation and shadows associated with the ridges are responsible for the well defined images on the IR imagery. The old, weathered ice pressure ridges do not, as a rule, provide sufficient radar reflection to permit discriminating them from the background backscatter which is generally relatively high from multi-year ice.

A large number of new ice pressure ridges are depicted on the multi-year and first-year ice of the Lincoln Sea radar imagery in Figure 6. This high presence of new ridges and the many small multi-year ice fragments indicate an area of intense deformation. The multi-year ice fragments resulted from the crushing action of larger floes colliding in the summer and late fall period before the first-year ice matrix formed between the floes. It is apparent that some of the larger floes were in the initial stages of deformation when freeze-up began. The floes seen here, which appear to have broken away from the main ice pack to the north, were probably drifting southward toward Robeson Channel before freezeup. The more consolidated area of multi-year ice on the right end of the imagery represents the edge of the main ice pack.

Many of those features which have been hypothesized to be frozen melt ponds are seen on the radar imagery in Figure 6 scattered over the multi-year ice floes. They appear as low radar return features with some having the smaller areas of high returns within the low return area.

2. Nares Strait Imagery

The imagery in Figure 7 helps to substantiate the hypothesis presented in Section IIIC concerning the effect of the snow depth/ice thickness ratio in the development of a radar backscattering surface at the snow-ice interface. It is evident that A and B are parts of the same frozen fracture, therefore presumably of the same age/thickness. But Area A has more snow cover and gives a higher radar backscatter than B. Other areas within this zone of level first-year ice possess minor differences in thickness and snow cover and the differences are evident in the radar return or image gray tone changes. A deeper snow cover in the rough areas adjacent to the multi-year ice floes, such as at C, contributes to an increased development of a radar backscattering surface. These areas are comprised primarily of first-year ice and are portrayed in a gray tone and texture very similar to the multi-year ice. The primary clue which enables discrimination of these areas from multi-year ice floes is shape or pattern analysis. These areas do not normally possess the characteristic rounded shape of the multi-year ice floes. This scene, as well as others shown, helps to illustrate that radar backscatter alone is not a sufficient criterion for identifying ice types or ice conditions. It is important that this be understood. Investigations which attempt to classify ice types using radar scatterometer techniques have been conducted. It appears that this technique would have a questionable accuracy and confidence level.

Figure 8 depicts deeply snow covered areas of rubble in Kennedy Channel which are comprised of small pieces of multi-year ice and first-year ice in a matrix of first-year ice. These areas have rounded shapes as well as an intermediate gray tone similar to multi-year ice floes. These areas could be identified erroneously as multi-year ice floes.

The only multi-year ice floe of significant size in the image in Figure 8 is located at A. Smaller, very light toned pieces of multi-year ice are depicted scattered about. The single medium sized multi-year ice floe located at A and the many smaller fragments scattered in this area are portrayed in unusually light gray tones. Similar very high radar backscatter multi-year ice fragments are depicted in Figure 7. They were fairly common in the Kennedy Channel imagery. One factor most of these feature have in common is their small size. Two possible explanations for the very high radar backscatter are offered. During extremely severe deformational activity, which is common in this area before and during freeze-up, some small floes and cake size pieces of multi-year ice may have been overturned and/or completely flooded with sea water. Overturned ice would present a radar rough surface which could have a comparatively high dielectric constant due to the presence of a newly formed ice with a relatively high salinity. Severe flooding of the ice surface could result in the entrapment of sea water on the surface. Its erosive action and high salinity would produce similar results.

The small iceberg shown in Figure 9, at A, cannot readily be identified on the radar imagery even though the radar shadow caused by this feature is clearly depicted at B. The bright lineations associated with the iceberg edges probably represent ridged sea ice bordering the iceberg. Other icebergs seen on the radar imagery were equally or more nondescript than this one. The signals received from the iceberg are a result of volume scattering from within the iceberg.

Figure 10A is a 50 nautical mile long radar image strip depicting ice conditions in southern Kennedy Channel. Hans, Franklin, and Crozier Islands are identified. Figure 10B depicts ice conditions along a 50 nautical mile strip over northern Kane Basin. Both areas are completely ice covered. The generally rounded shape and light gray tone of the multi-year floes permit their easy discrimination from the background ice matrix. The multi-year ice floes seen here are, as a rule, much smaller than those shown in the Lincoln Sea (Figure 6). This is attributable to intense floe interaction and deformation which resulted during rotational and translational floe motion in their southerly transit from the Lincoln Sea through the relative narrow Robeson and Kennedy Channels. Maximum ice drift occurs during the summer season, particularly during late summer when ice concentrations reach a minimum. Floe interaction and deformation may reach a maximum at this time and during fall freeze-up. The intensity of ice deformation is further evidenced by the high concentration of rubble zones or areas comprised primarily of a combination of ice blocks, hummocks, and ridges and having relatively high (intermediate gray tone image) and generally uniform radar backscatter due to a combination of multiple reflections caused by the broken ice conditions and a radar reflective zone developed as a result of heavy snow cover. The dark gray tones represent areas of thinly snow covered first-year ice which have undergone very little, if any, deformation. Very large areas of first-year ice containing very little multi-year ice are depicted at the far right end of Figure 10A and in the center portion of Figure 10B. The intricate network of new ice ridges portrayed in the first-year ice zone in Figure 10B presents strong evidence of differential motion within this area of Kane Basin after fall freeze-up began.

It appears that the very large floe lodged against Hans Island was being broken up prior to freeze-up. The ramming action of drifting floes from the north probably caused this deformation. The big floes which appear to have come from this large floe are seen eastward of Hans Island in a matrix of smooth first-year ice which must have begun forming soon after the deformation of the larger floe began.

A number of those features which have been interpreted as large frozen melt ponds are apparent in this area as well as in the Lincoln Sea. Several of the most outstanding ones have been annotated in Figure 10. Many smaller ones are present, but are not easily seen at this imagery scale. The size, shape and pattern of melt ponds on a floe are strongly related to the floe age. Larger sizes, more rounded shapes, and irregular patterns are usually associated with older floes.

There are many identifiable areas of undeformed first-year ice which could possibly serve as surfacing sites (skylights) for submarines operating under the ice. The primary criteria determining selection of these areas are size, ice thickness, and bottomside roughness.

The 50 nautical mile section of radar imagery shown in Figure 11, shown with a strip of infrared scanner imagery (negative print) taken two days earlier, extends over the southern half of Kane Basin. The photographs shown were taken at the north boundary of the North Water Polynya several hours after the radar imagery was taken. A portion of the North Water Polynya, the well known perennially recurring area of open water located in Smith Sound and the southern end of Kane Basin, is shown on the left end of the two imagery strips. New ice types which have been deformed and dissipated by wind, currents, and wave action are scattered over the Polynya. Evidence of waves can be seen in the thinly ice covered areas which appear in a patchy intermediate gray pattern. The bright lineations near the north boundary of the Polynya represent strings and belts of fractured and rafted ice such as that shown in the photographs. The uniformity of fragment size in

the broken thin ice field (as seen in photographs B and C) indicates that this deformation was caused by wave or swell action.

Rafting in the very thin ice which lies between the fractured ice and first-year ice zone bordering the north side of the Polynya is attributed to pressures caused by the wind driven broken ice field pushing against this area. The band of very thin ice adjacent to the north boundary has been extensively rafted as shown by photographs C, D, and E in Figure 11. The broad zone, five to six miles wide, of relatively undeformed first-year ice bordering the north side of the Polynya is interpreted as a more recent first-year ice formation than the first-year ice matrix depicted among the multi-year floes. It appears that this formation may have replaced ice which was broken and removed by earlier action of waves, winds and currents. The second broad zone of first-year ice shown farther north in Figure 11 also represents a more recent first-year ice formation. It is speculated that the older ice field between the two broad bands of first-year ice shifted south about eight miles sometime after freeze-up and that the two more recent bands of first-year ice formed after that shift. The ice in Smith Sound in the zone between Pim Island and Kap Ingefield, Greenland, acts as a dam which retards or stops ice flow from the north. If this ice is removed by wave, wind and/or current actions, then a southward movement of ice located north of here would be possible. Evidences seen during this investigation indicate that sea swell and/or waves may be an important agent in the continual development or sustenance of the ice free or near ice free conditions which prevail in the North Water Polynya. While winds and currents may be responsible for evacuation of the ice, swell and/or wave actions may be largely responsible for the continual breaking up of the newly formed ice fields in this area.

The infrared strip imagery shown in Figure 11 is representative of the relative surface thermal pattern. The warmer surfaces are represented in a darker gray tone. Some cross-correlations are shown to provide guidance of further comparison since gross geometric distortions exist on the thermal imagery. The multi-year ice floes, particularly the smaller ones, are much easier to discriminate on the radar image. The level areas of first-year ice between the multi-year ice floes appear to be the warmest areas (dark gray) on the thermal imagery. These areas probably represent the most recent ice cover which formed on small polynyas resulting from deformational activity within the ice field after the initial freeze-up. These areas also appear darkest (low radar return) on the radar imagery. The two broad zones of first-year ice appear relatively cool on the thermal imagery. This is probably due to a shifting of the IR system dynamic range which resulted from looking at a fairly uniform thermal surface over the total field of view. Also the snow depth here may have been partially accountable. Note the relatively high backscatter indicated on the radar image of these areas. This has been attributed to the development of a radar reflective layer at the snow-ice interface.

3. Baffin Bay Imagery

The prevailing ice conditions in Baffin Bay, as discussed in Section IIIC, differ from ice conditions in the Lincoln Sea, Kennedy Channel, and Kane Basin. In Baffin Bay there is a dominance of the early stages of ice development or thinner ice types. These variable conditions produced a wide range of radar backscattering from areas of ice possessing only minor differences in thickness and age.

Because of these variabilities and the complexities of the ice conditions, interpretation of the Baffin Bay imagery is much more difficult than the more typical sea ice imagery of the Lincoln Sea,

Kennedy Channel, and Kane Basin. In some instances, in Baffin Bay, areas of ice which appear very similar on the visual photography display radically different backscattering characteristics on the radar imagery. Conversely, some areas which display a visually different ice cover appear to have similar backscattering charcteristics on the radar. The following examples of comparative photography and radar imagery illustrate a variety of radar returns associated with Baffin Bay ice and serve to illustrate the complexities involved in interpretation.

Cross-correlating the radar image and the photography in Figure 12 it is seen that the thicker first-year ice, as at A, is depicted on the radar image in a smooth textured light gray tone indicating that the reflective surface is composed of a rather uniform distribution of small scatters. This is not typical of the first-year ice portrayed earlier except in the cases where a heavy snow cover existed, deposited in areas of broken ice formations. The snow cover here does not appear very deep, however, the first-year ice here appears thinner than that shown in Kennedy Channel and the Lincoln Sea. The existing ratio of snow depth and ice thickness may be optimum for development of a good radar reflective surface as hypothesized earlier. Delineation of ice pressure ridges on this first-year ice is almost completely precluded because of the high background noise. The thinner first-year, as at B, which appears to be nearly snow free on the photography, is generally portrayed in very dark or intermediate gray tones on the radar image. Ice ridges in these areas are easily delineated. The youngest, thinnest ice in this scene, as at C, is identified as nilas. This ice is snow free and appears on the radar image in a gray tone slightly lighter than the thinner, snow free first-year ice, but darker than the snow covered first-year ice at A. A small area of young ice at D provides the highest radar backscatter on the imagery. With close examination of these images it becomes evident that there are variations from the above gray tones for a given ice type. This becomes more apparent in subsequent illustrations which will serve to point out the extreme difficulty in accurately classifying ice types using radar backscatter criteria in this environment. Pattern analysis does little to aid the analyst.

The area shown in Figure 13 is comprised of ridged first-year ice with two parallel fractures, one at C, covered with nilas, the other at E, covered with young ice. The level thinly snow covered first-year ice at A in this area gives a comparatively low radar return. The more heavily snow covered first-year ice, as at B, gives a higher radar return. Ridges are not easily discerned. The nilas on the most recent fracture, at C, gives a radar return similar to the level thinly snow covered first-year ice. This is evidence that the very earliest ice forms are sufficiently rough to provide some backscatter. The narrow fracture, D, within the larger fracture is more preceptible on the radar image than the photography. It provides no significant return and is probably ice-free. The most interesting phenomena here is the very high radar return from the young ice covered fracture at E. The young ice is snow free. Similar high returns were evident on a number of young ice covered fractures like this in Baffin Bay. It is possible that this area of relatively thin ice is covered with a high density of ice flowers. These are delicate tufts of frost or rime resembling flowers that occasionally form in great abundance on surface ice around salt crystals which act as nuclei. Atmospheric conditions (quiescence and dew point near to air temperature) favorable to the development of these features existed in this area on the day the data were collected. Ice flowers were observed on thin ice by personnel working on the ice at a location north of this site on this same day. An ice flower covered surface should offer criteria necessary for good radar return, a rough surface with high dielectric constant.

Cross correlation of the photography and radar imagery in Figure 14 further illustrates that similar ice types may have different radar backscatter characteristics or, conversely different ice

types may have similar radar backscatter characteristics. The areas marked A represent snow covered first-year ice which is probably greater than one meter thick. This is the thickest ice in this scene and it appears in a very light gray tone on the radar imagery. The areas marked B appear similar to A on the photography, in fact in some cases A and B share the same floe. The B areas are portrayed in the darkest gray tone on the radar imagery. The areas marked B may possess less snow cover and/or have a different thickness from the A areas, but this is difficult to discern from the photography. In any event, it appears that the radar is revealing information not readily available on the photograph even though the ability to interpret the information does not exist.

Areas marked C appear very similar in gray tone on the radar imagery. However, these areas appear different from each other on the photography. C_1 and C_3 represent nearly snow free thin first-year ice (probably 30-40 cm thick). C_2 represents a dark nilas less than 5 cm thick, and C_4 represents a light nilas 5-10 cm thick. In this case the similarity of gray tones on the radar imagery precludes discrimination or confident interpretation of these ice types. Shape or pattern analysis does not aid in the interpretation here. The brightest areas on the radar image such as D_1 and D_2 represent young ice formations which are slightly thicker than the light nilas at C_4.

Ground truth studies could do much to explain the reason for the variations in radar return discussed here. However, in some cases the explanations may not help the interpreter to decipher the data.

The single channel of radar imagery shown in Figure 15 represents a section about 50 nautical miles long in northern Baffin Bay. With the exception of the single multi-year ice floe at the northern end of this strip, this area of ice is entirely comprised of first-year ice and younger states of ice development. Some open water features are present. Although ice conditions along this strip are generally similar, there are many more variations in gray tone and texture and much more detail is portrayed on the northern half of the radar strip. On the southern half of the strip there is a prevalance of an unusually high, homogeneous radar backscatter associated with a large majority of the first-year ice. This has been attributed to the development of a good radar reflective surface resulting from a heavier snow cover (See Section IIIC). This situation prevailed for about another 40 miles southward of this strip.

To further illustrate the complexities of Baffin Bay sea ice interpretations, a number of ice types and features in Figure 15 have been correlated on the photography and radar imagery and identified in the lists shown.

It seems evident that local weather conditions such as fluctuating air temperatures, dew point, and precipitation have played an important role in the formation of radar reflective surfaces in the Baffin Bay imagery shown here. Major differences in radar reflective characteristics of the ice types shown within Baffin Bay and those areas further north (Nares Strait and Lincoln Sea) lend much substance to the idea that local atmospheric phenomena are responsible. If this is true, then it becomes apparent that the development of interpretational keys will be a very difficult task for this area or other areas within the marginal ice zone where wide fluctuations in weather conditions are common. This is true because in these areas there is a greater concentration of the younger stages of ice development whose physical properties are more susceptible to weather changes than the older, thicker ice forms. Even if surface truth exercises document the reasons for the anomalous radar returns seen here, future radar interpretations may not benefit widely because of the

ambiguity of the returns. However, determination of the cause may prove useful in the evaluation of other remote sensing systems.

A look at the radar imagery in Figure 15 shows that single ice pressure ridges and areas heavily covered with ridges can usually be detected and identified on the northern half of the strip. However, these features, for the most part, are completely obscure on the southern end of the strip due to the high background reflection. Open water fractures and thin ice covered fractures, regardless of their gray tone, are usually identifiable because of their characteristic linear shapes and association with other features. Most individual ice **floes** cannot be accurately delineated on the radar strip because of the ambiguity of radar returns from within a floe and the adjacent ice. Determination of ice concentration could be done with reasonable accuracy on the northern half of this strip, but on the southern half of the strip many of the very low return areas of first-year ice could easily be misinterpreted as open water polynyas. If the generally homogeneous light gray tone present on the southern section of the radar image is due to a heavier snow cover, as hypothesized, this information may be useful to icebreaker operations. Snow cover on the ice absorbs much of the shock imparted by icebreakers ramming the ice, thus reducing their effectiveness.

IV. SUMMARY

The ability to interpret sea ice features and conditions, with some reservations, was generally very good in the more northerly arctic areas of Nares Strait and the Lincoln Sea. Interpretation of the more predominant young stages of ice development found in Baffin Bay was much more difficult. This difficulty was due to the characteristic homogeneous low return associated with the many young stages of ice development and also to an anomalously high homogeneous return associated with some ice conditions in Baffin Bay.

Multi-year ice forms are generally one of the easiest targets to discriminate because of their rather homogeneous intermediate to high backscatter and characteristic shapes. The younger stages of ice development such as first-year ice, young ice, nilas, etc., can be easily discriminated from the older, thicker multi-year ice, but often cannot be discriminated from each other based on backscatter information. From this it can be seen that even though fractures within the ice field were usually identifiable, the stage or stages of ice development (or water) which cover a fracture cannot always be identified. Sometimes the stage of ice development can be strongly inferred using other information. A high incidence of discernible pressure ridges on a low return background would strongly indicate that the background is thick first-year ice. Evidence of ice rafting in the imagery usually indicates an area of thin first-year ice, or more likely, earlier stages of ice development. So, it is apparent that stages of ice development can often be inferred through knowledge of their characteristic associations with other more identifiable features. It has been shown that radar backscatter alone is not always a sufficient criterion for identifying or classifying stages of ice development. This was found to be particularly true in the Baffin Bay environs and this truth can be logically extrapolated to include other areas within the marginal ice zones.

New ice pressure ridges and hummocks usually provide a good radar return. This fact, along with their linear shapes, make them easily identifiable targets when their adjacent backgrounds provide a relatively low backscatter. New ridges are extremely difficult, if not impossible, to discriminate when a high backscattering ice terrain is present. Old weathered pressure ridges and

hummocks which provide the topographic relief so common to multi-year ice usually provide a backscatter similar to their multi-year ice backgrounds, hence often remain obscure or undetected. This is true even though the surface slopes of some of these old pressure ridges provide an optimum angle of incidence for maximum radar return. This fact lends credence to the suggestion that radar returns from multi-year ice are largely due to volume scattering.

It appears that the high quality of engineering parameters in this radar system have enabled discrimination and identification of many frozen melt ponds on multi-year ice floes. These areas provide a low radar return. It is believed that the radar energy passes through the relatively tranparent fresh water ice comprising the frozen pond and is attenuated in the multi-year ice below. Bright returns seen within the dark area of some of these ponds have been hypothesized to represent reflections from thaw holes (where ponds melt through to underlying water). The bright return is attributed to a strong reflection at the fresh ice/new sea ice interface.

This analysis has revealed that under certain conditions snow cover may play an important role in the development of a strongly radar reflective layer at the snow-ice interface. It is believed that proper balances of ice thickness, snow depth, air temperature, and time will enhance conditions at the snow-ice interface which are conducive to the formation of a high dielectric, radar rough layer which provides a high radar backscatter. Evidences of this condition are suggested in many heavily deformed areas of first-year ice where snow cover is deeper due to the deposition of wind blown snow, and also in some portions of Baffin Bay where it appears that the snow cover on much of the oldest first-year ice is much deeper than the adjacent areas. This may be attributed to local precipitation. In both cases a much higher radar backscatter, than normally expected, was produced.

There is a need for surface truth observations in order to confirm and answer many of the hypotheses and questions forwarded in this interpretational analysis. The formulation of hypotheses which attempt to explain backscatter characteristics, has revealed new avenues for research in the sea ice environment. Particular reference is made to electromagnetic windows in the sea ice cover in the form of frozen melt ponds. But in addition to these specific features, the possibility of electromagnetic transmissions through a large portion of the vertical sections of old multi-year ice floes cannot be overlooked. Although sufficient evidence was not available during this analysis to determine the source of radar reflections from multi-year ice, it appears evident that volume scattering and/or some subsurface layers are providing the primary reflective zone. The upper portions of old multi-year ice floes have experience much reconstituion. Salts have been drained and/or leached from the ice and much of this material has been replaced with fresh water during the melting seasons. The result may be that a large portion of this reconstituted ice is at least partially transparent to electromagnetic energy, particularly the longer wavelengths. If this is true, air to submarine communication through sea ice may be made possible by penetrating an antennae through the lower, higher conductivity layer of sea ice, which acts as a electromagnetic shield, and receiving (or transmitting) through the upper, more transparent layers. Field experiments could reveal the feasibility of this technique.

The reasons for the anomalously high radar backscatter in Baffin Bay so strongly associated with normally low radar reflective ice conditions could be determined through ground truth observations. If the unusually high backscatter is strongly related to climatic conditions as has been speculated, it could be important to know whether these backscatter surfaces are of a transient nature. Knowledge of the presence of this scattering layer could be useful to evaluation of other

sensors. If it is a transient phenomena, interpretational techniques could be keyed accordingly. In addition, the presence or absence of the phenomena could provide a feedback to earlier weather conditions and also may give some clue as to the order of magnitude of ice thickness within the younger stages of ice development.

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GLOSSARY OF SEA ICE TERMS

First-year ice: Sea ice of not more than one winter's growth, 30 cm - 2 m thick.

Floe: Any relatively flat piece of sea ice 20 m or more across.
Floes are subdivided according to horizontal extent as follows:
Giant: Over 10 km across
Vast: 2-10 km across
Big: 500-2000 m across
Medium: 100-500 m across
Small: 20-100 m across

Fracture: Any break or rupture through ice resulting from deformation processes. Length may vary from a few meters to many kilometers.

Hummock: A hillock of broken ice which has been forced upwards by pressure. May be fresh or weathered.

Ice cake: Any relatively flat piece of sea ice less than 20 m across.

Melt pond: A depression on sea ice filled with melt water. During the summer, snow and ice may absorb more heat than they radiate with the result that melting occurs and small puddles are formed. Puddles grow individually or by running together.

Multi-year ice: Old ice up to 3 m or more thick which has survived at least two summer's melt. Hummocks are relatively smooth and the ice is almost salt free. Melt pattern consists of large interconnecting irregular puddles and a well developed drainage system.

New Ice: A general term for recently formed ice composed of ice crystals which are only weakly frozen together.

Nilas: A thin elastic crust of ice, easily bending on waves and swell. Has a matte surface and is up to 10 cm thick.

Polynya: Any nonlinear shaped opening enclosed in ice. Polynyas may be covered with early stages of ice development. Submariners refer to these as skylights. If it recurs in the same position every year it is called a recurring polynya.

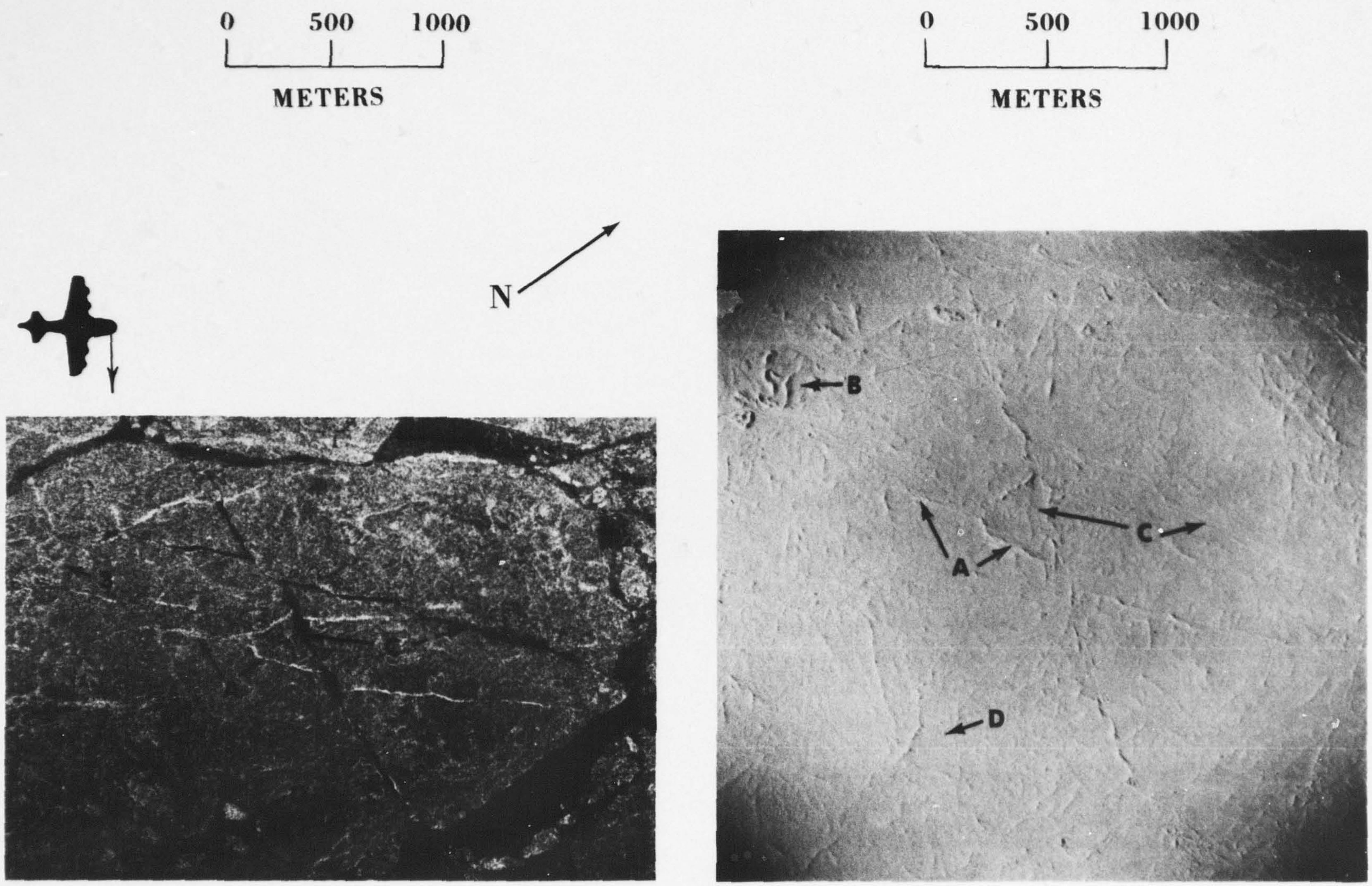
Pressure ridge: (See Ridge).

Ridge: A line or wall of broken ice forced up by pressure. May be fresh or weathered.

Thaw hole: Vertical hole in sea ice formed when surface puddles melt through to the underlying water.

Young ice: Ice in the transition stage between nilas and first-year ice, 10-30 cm thick.

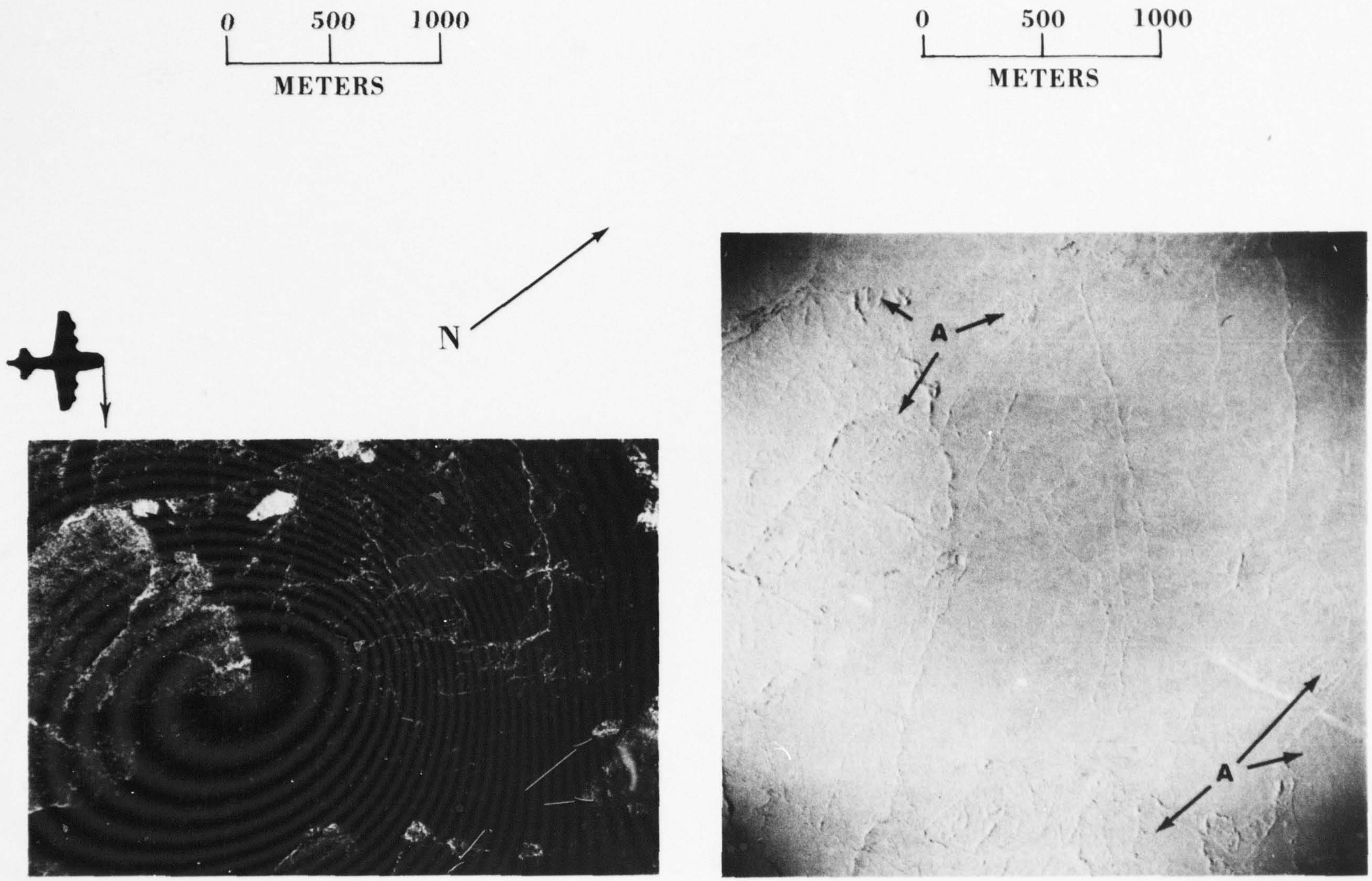
Figure 1 Areas of Radar Coverage, 7 May 1977



RADAR

AERIAL PHOTO

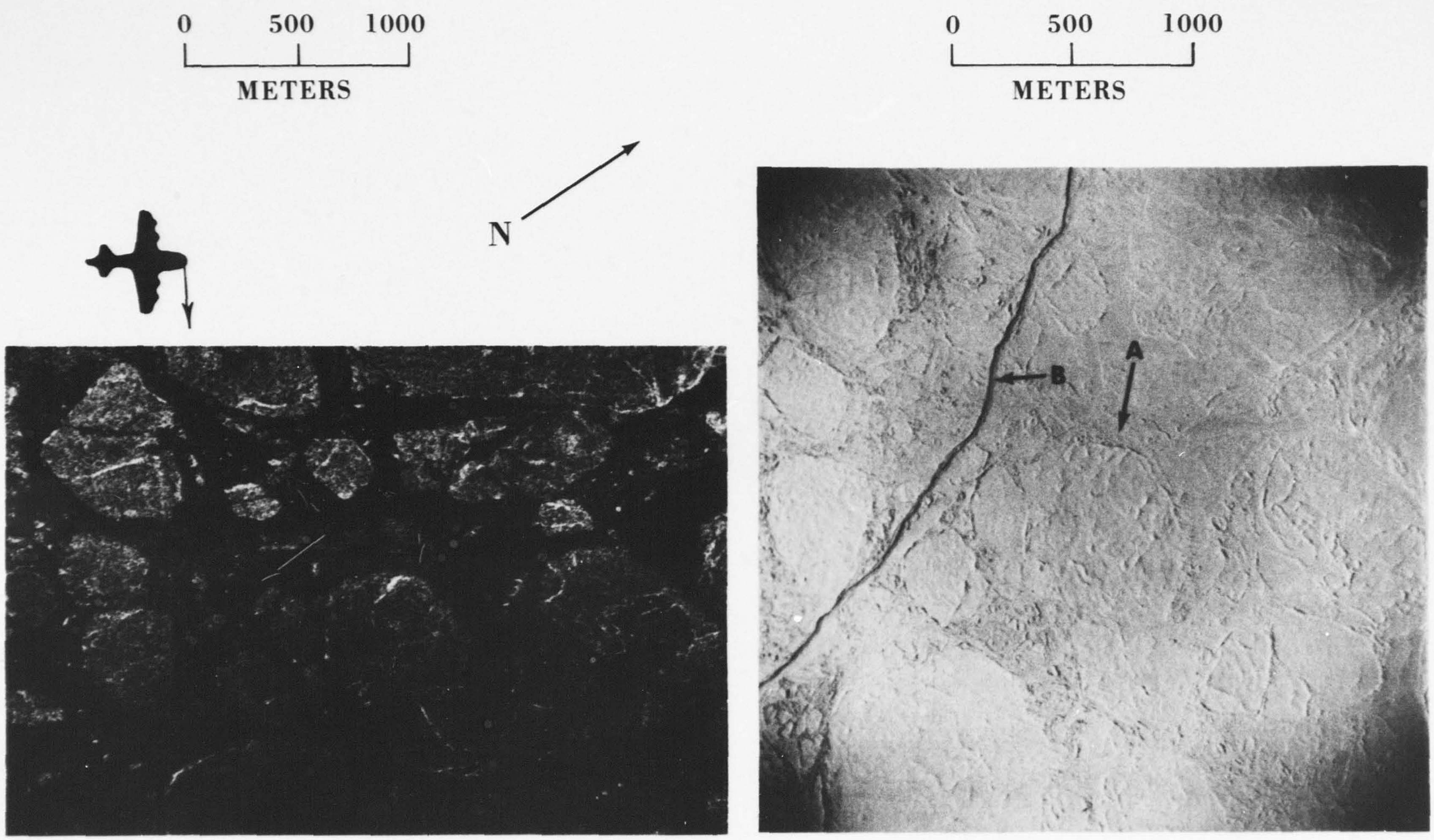
Figure 2 Comparison of Radar Imagery and Aerial Photography – Lincoln Sea



RADAR

AERIAL PHOTO

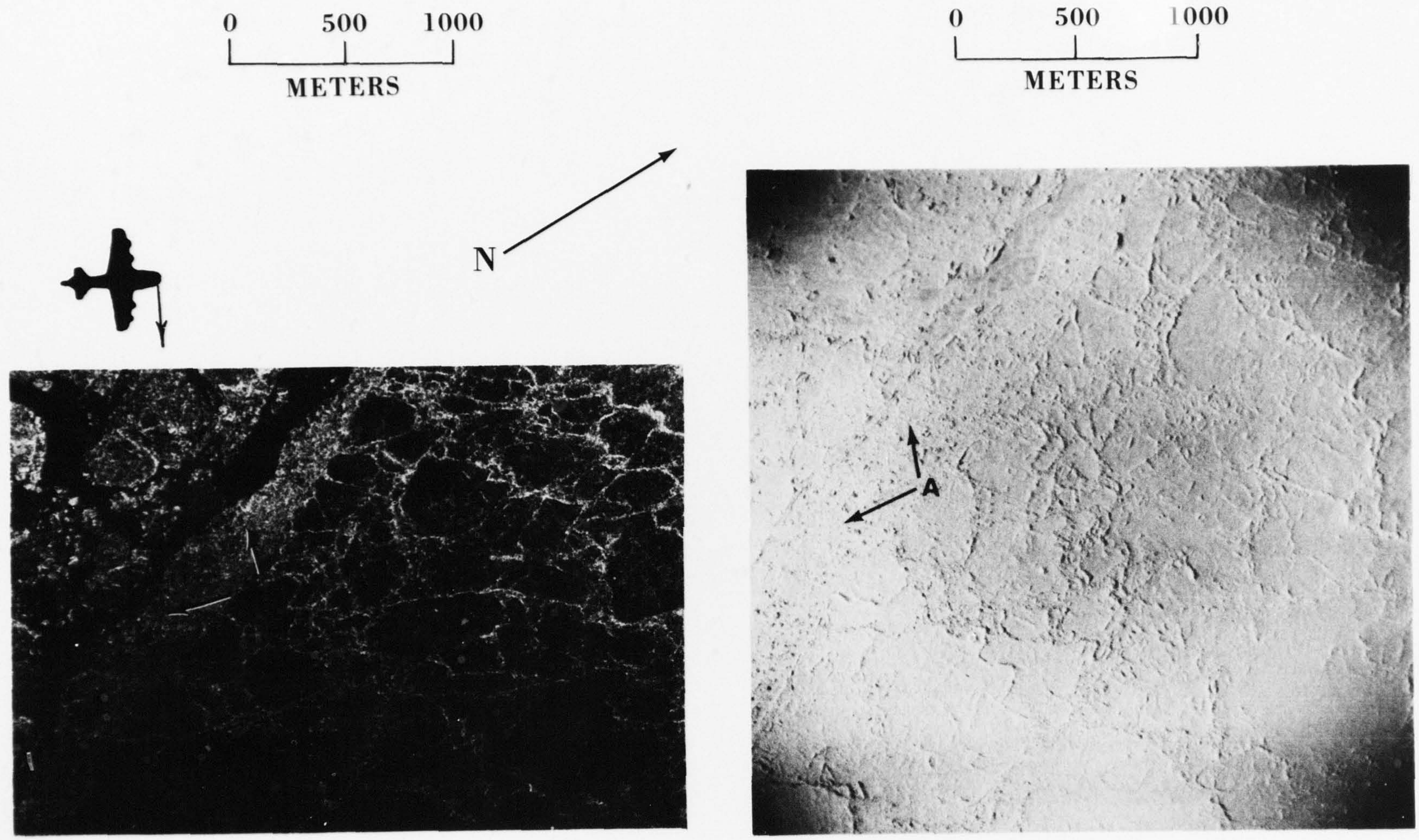
Figure 3 Comparison of Radar Imagery and Aerial Photography — Lincoln Sea



RADAR

AERIAL PHOTO

Figure 4 Comparison of Radar Imagery and Aerial Photography – Lincoln Sea



RADAR

AERIAL PHOTO

Figure 5 Comparison of Radar Imagery and Aerial Photography — Lincoln Sea

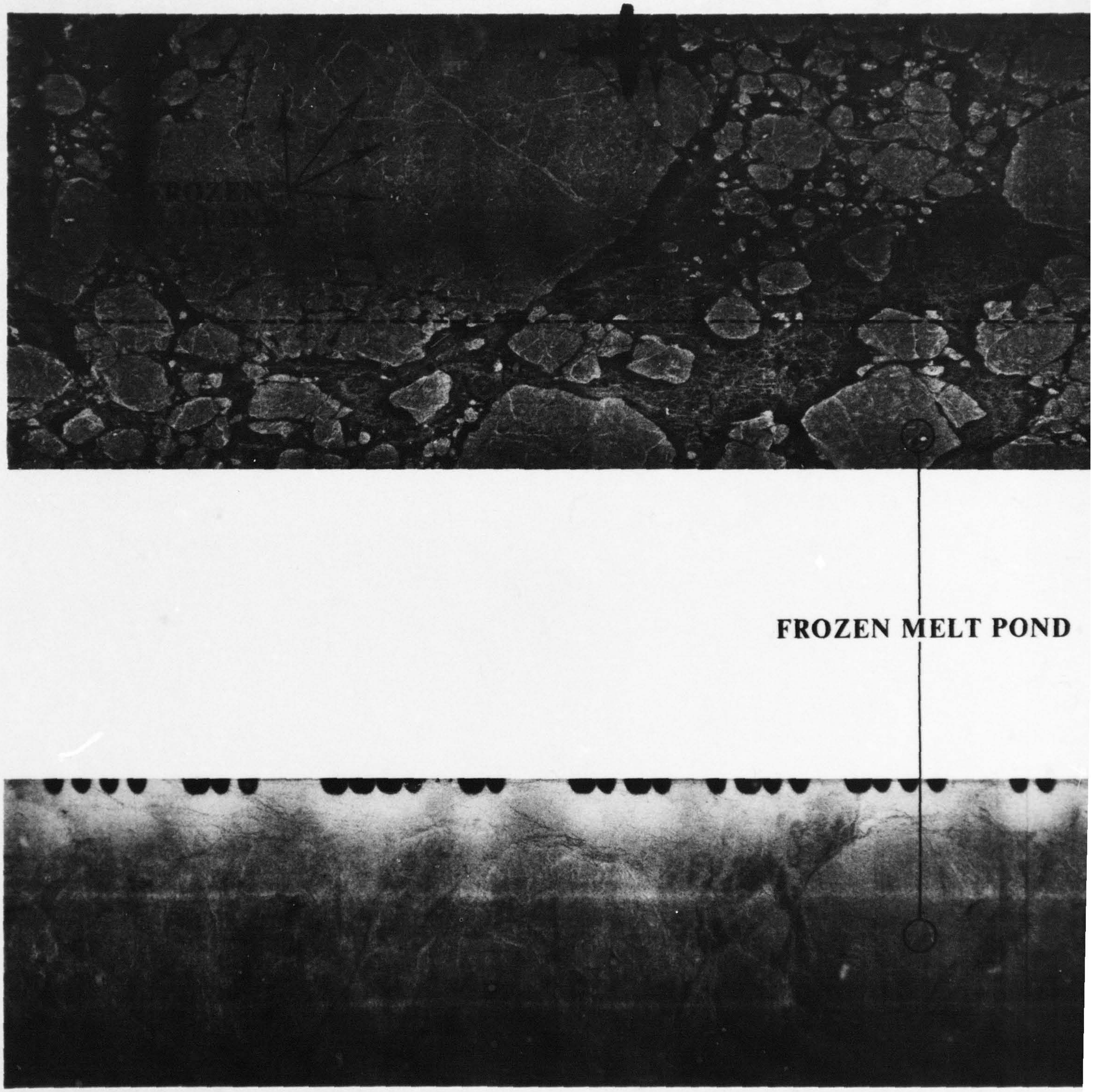
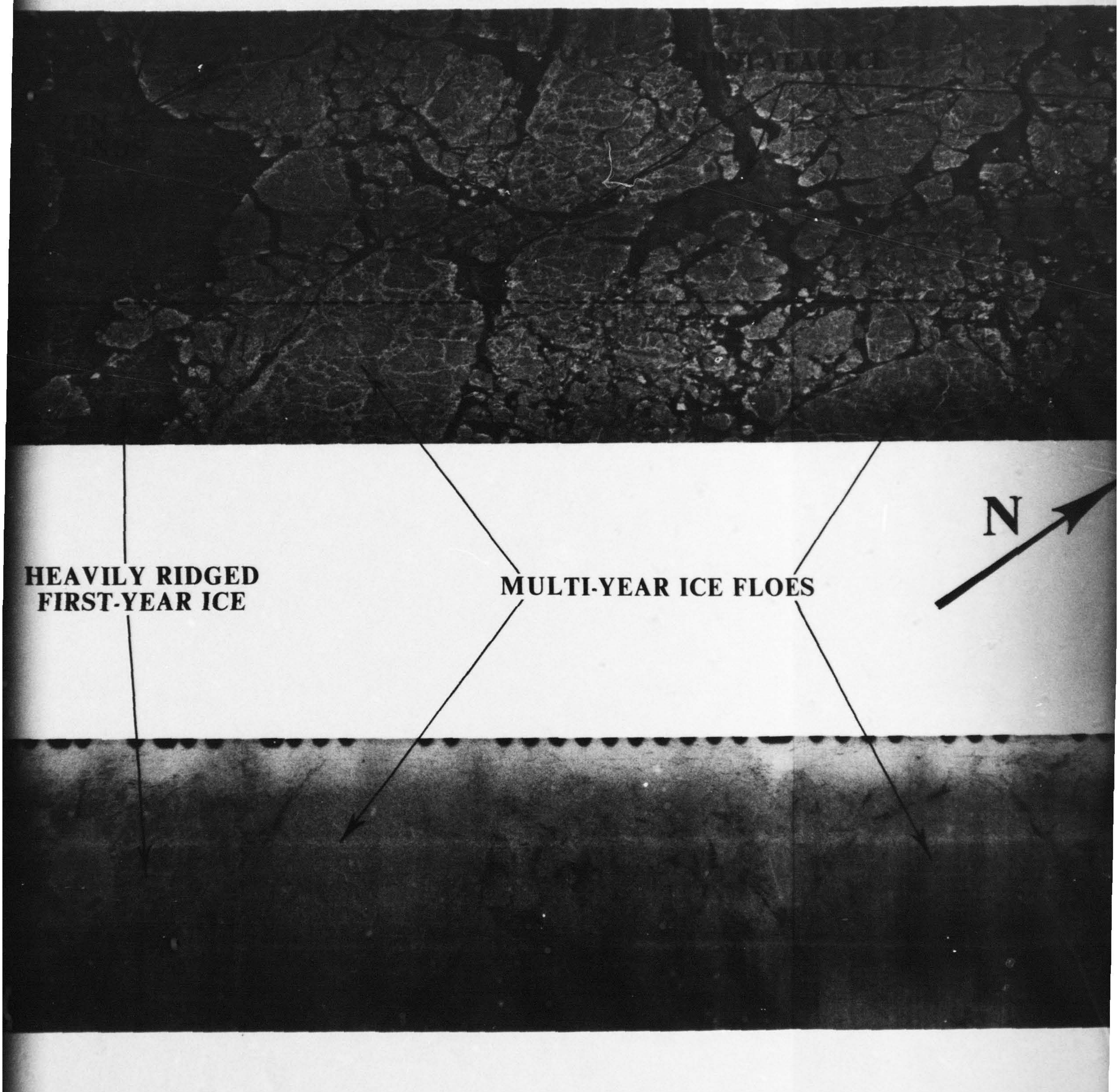


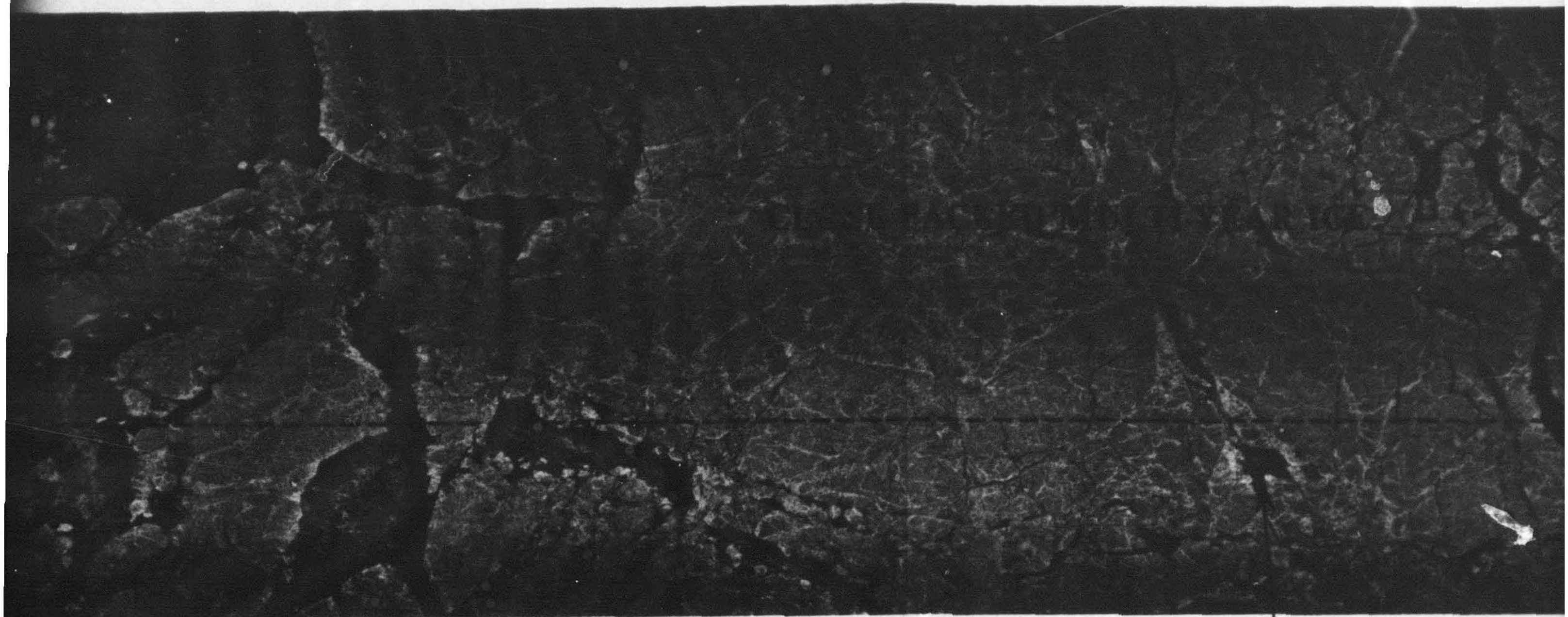
FIGURE 6. COMPARATIVE RADAR IMAGERY (TOP) AND INFRARED SCA

NER IMAGERY (BOTTOM) TAKEN OVER THE LINCOLN SEA, MAY 1975.

2



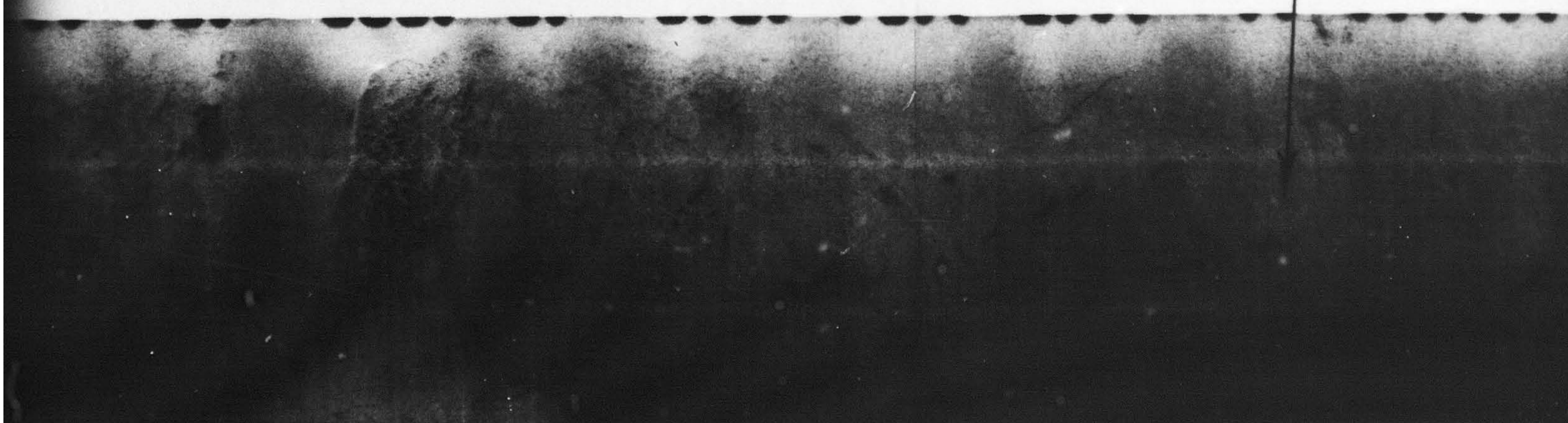
3

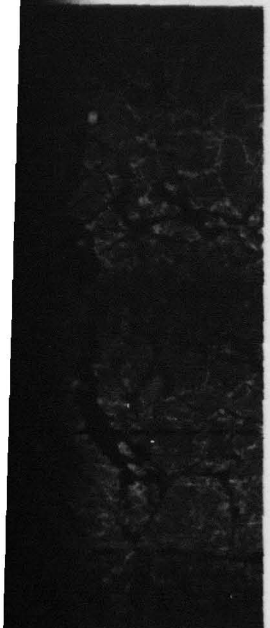


0 5

RADAR SCALE (N.M.)

HEAVILY SNOW COVERED
FIRST-YEAR ICE NOT
IDENTIFIABLE ON IR IMAGE





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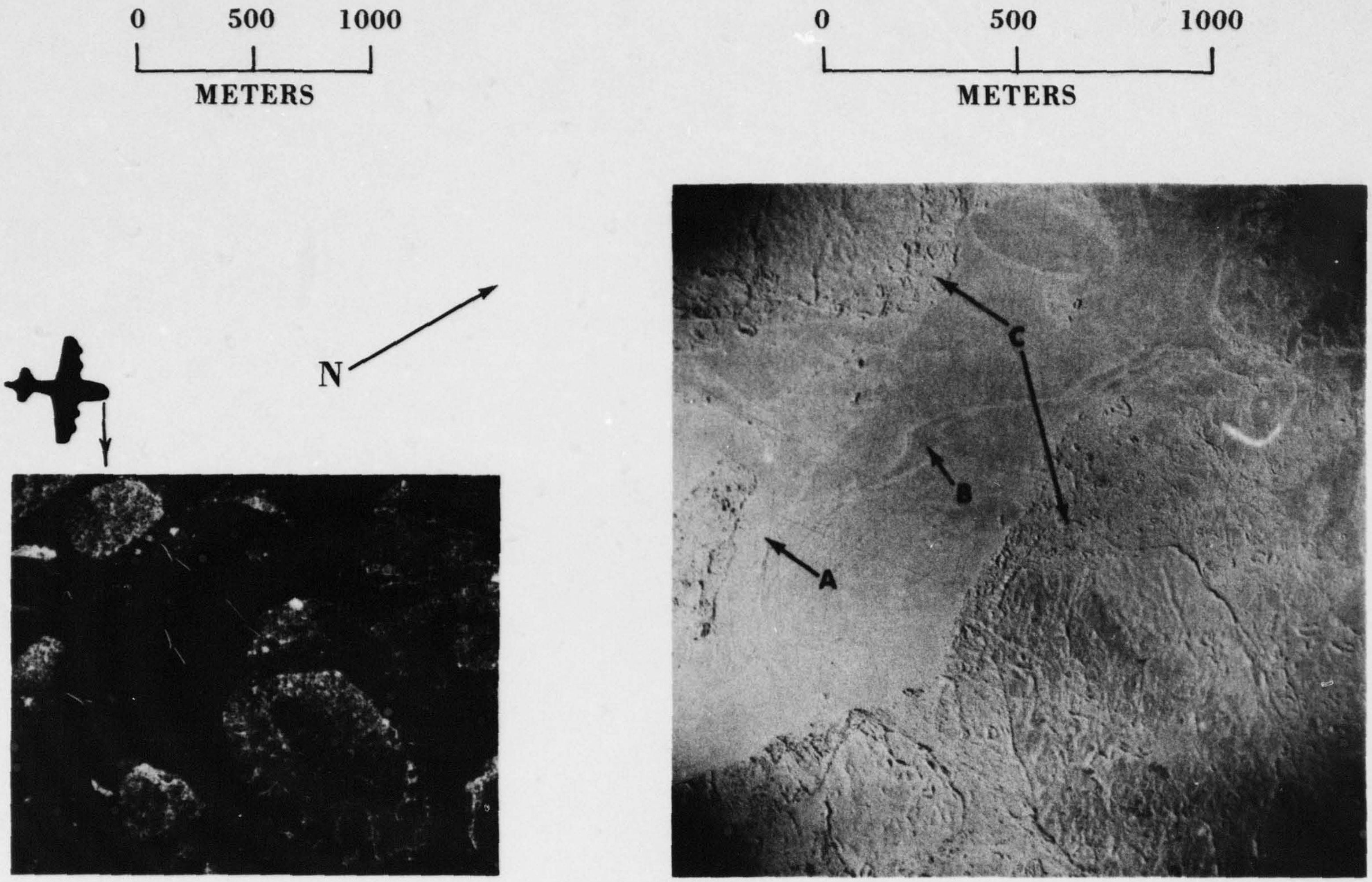


RADAR

AERIAL PHOTO

Figure 7. Comparison of Radar and Aerial Photography – Kennedy Channel

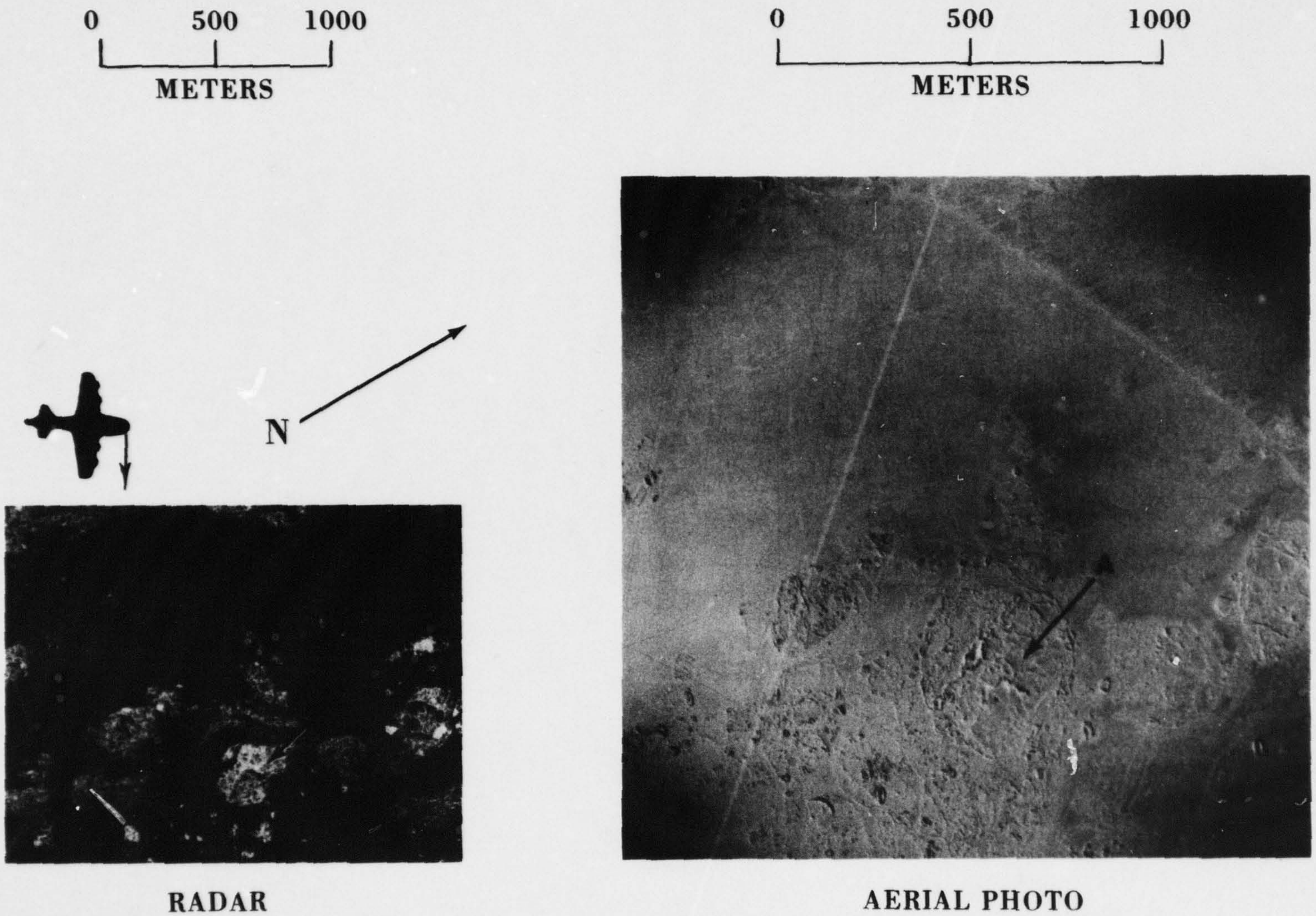
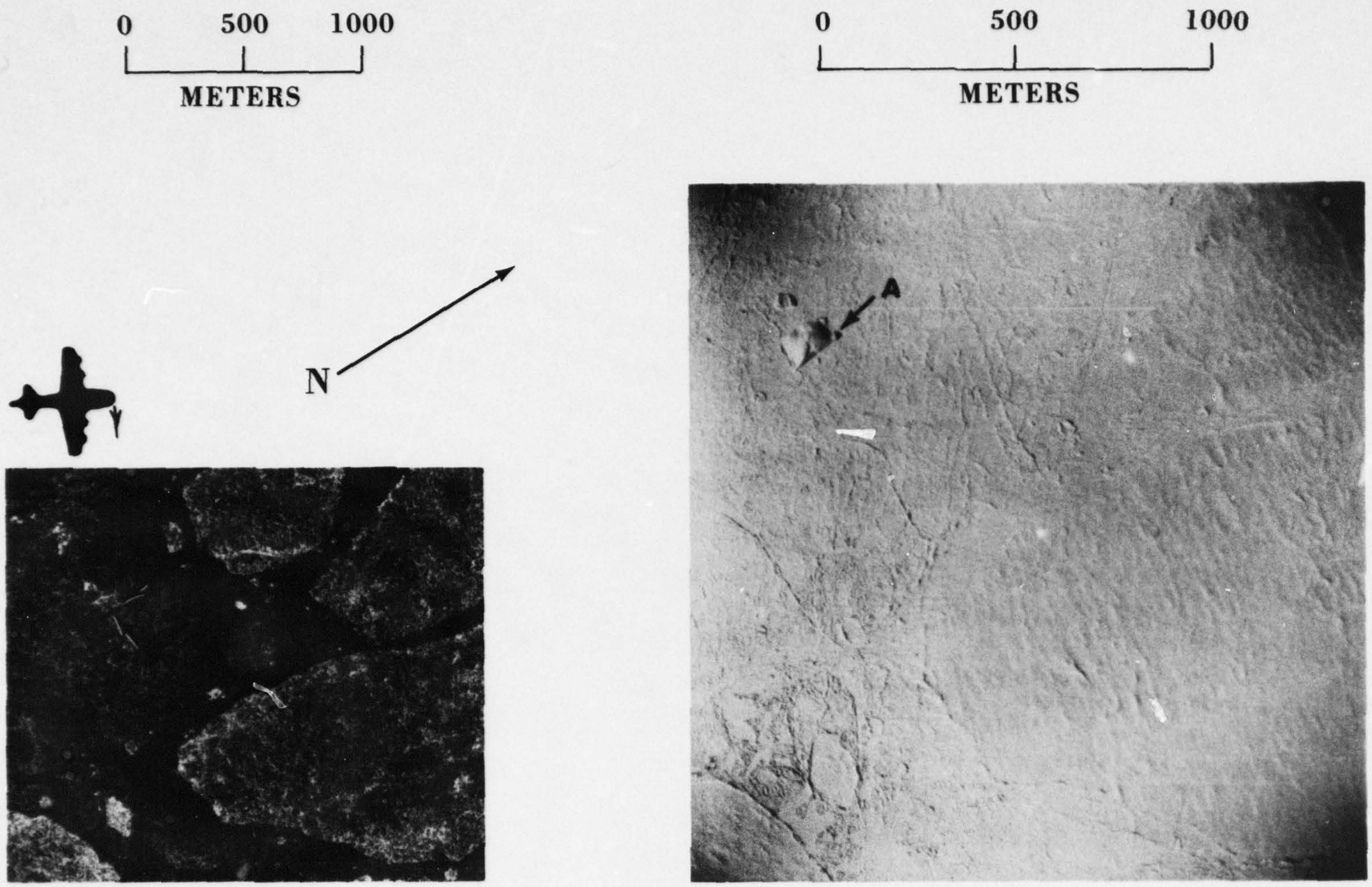


Figure 8. Comparison of Radar Imagery and Aerial Photography – Kennedy Channel



RADAR

AERIAL PHOTO

Figure 9. Comparison of Radar Imagery and Aerial Photography – Kennedy Channel

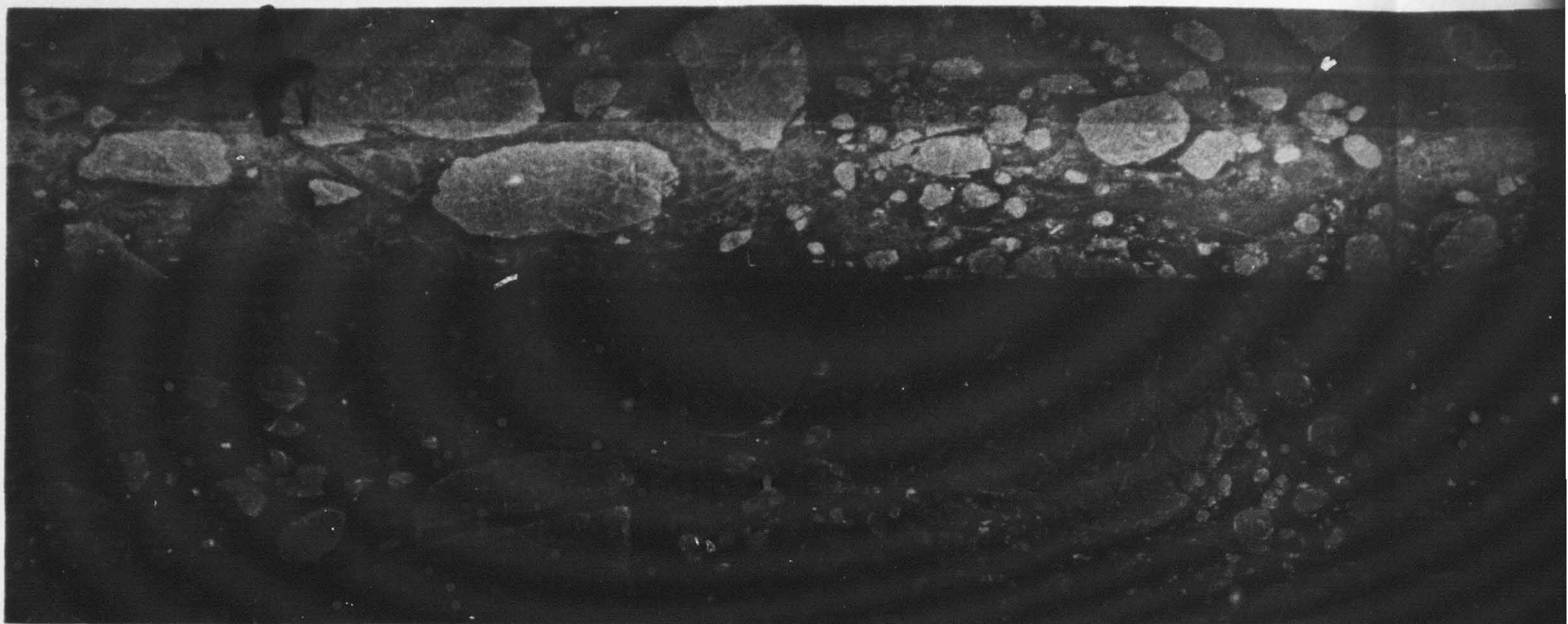


FIGURE 10A. RADAR IMAGERY TAKEN OVER KENNEDY CHANNEL,

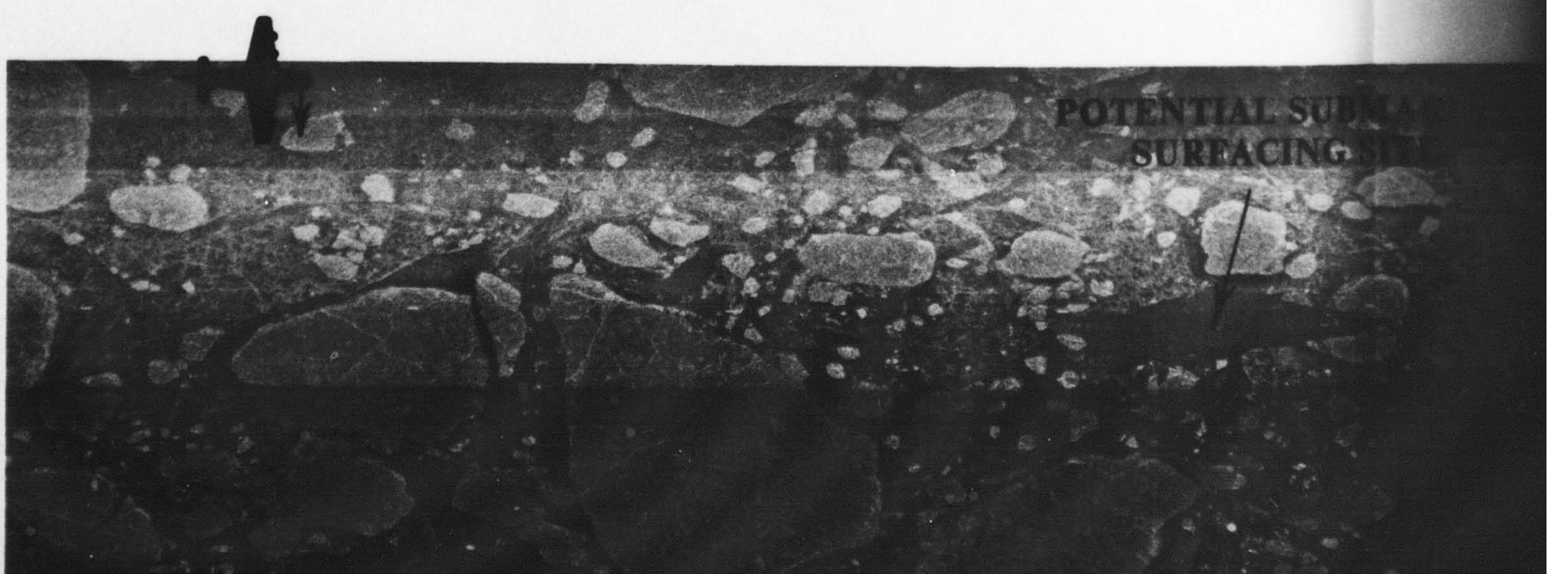
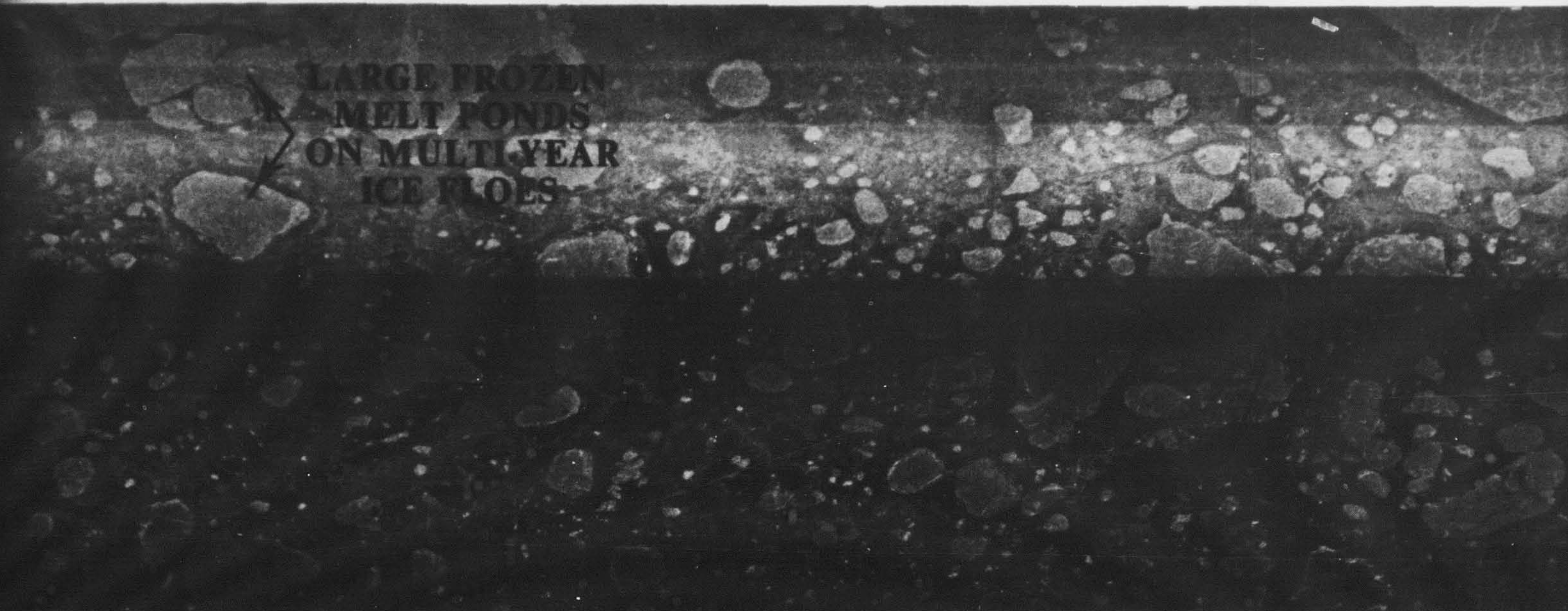


FIGURE 10B. RADAR IMAGERY TAKEN OVER NORTHERN PORTION



, MAY 1975.

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NA

N OF KANE BASIN, MAY 1975.

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NAUTICAL MILES

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HANS ISLAND


EN MELT PONDS
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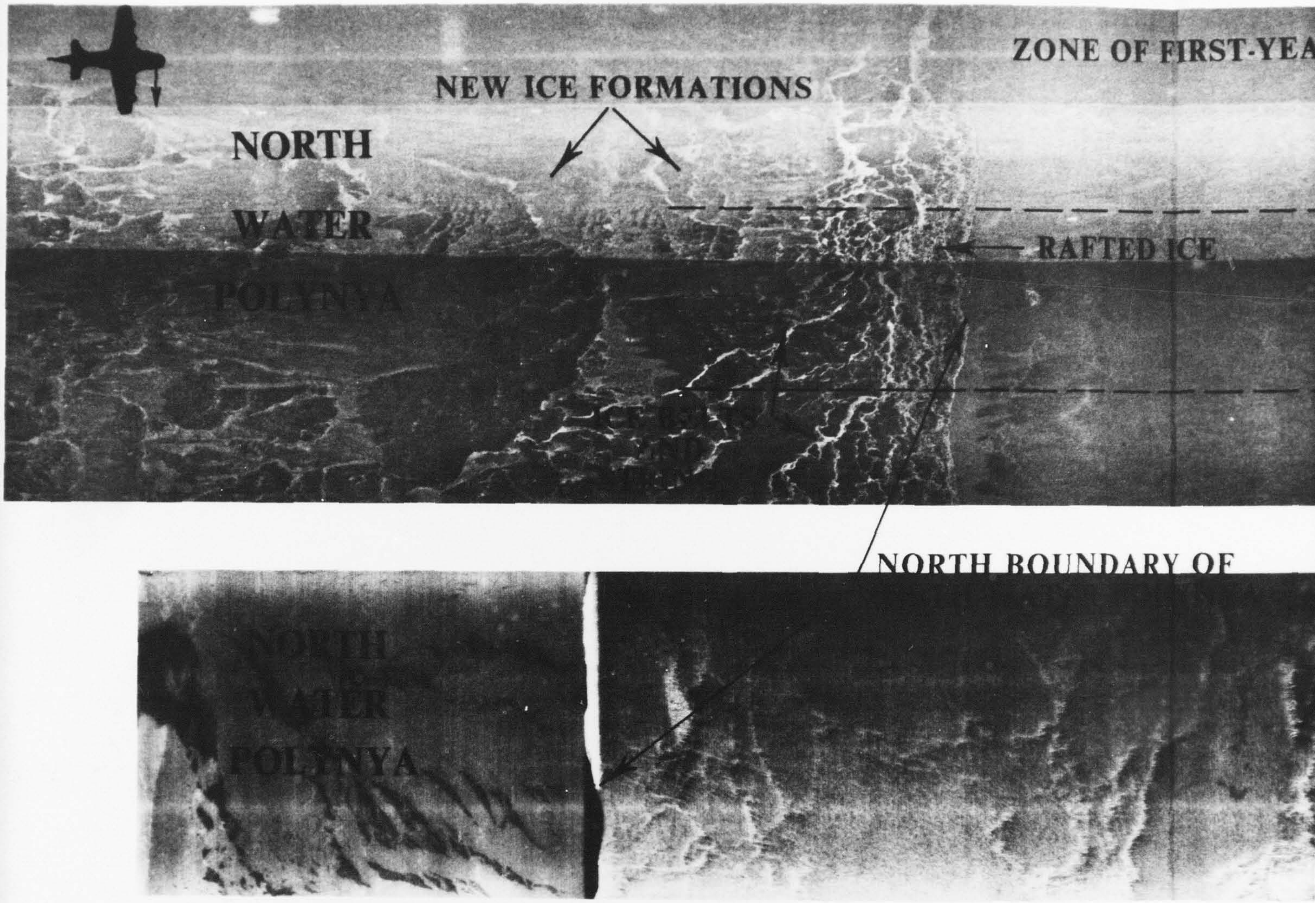
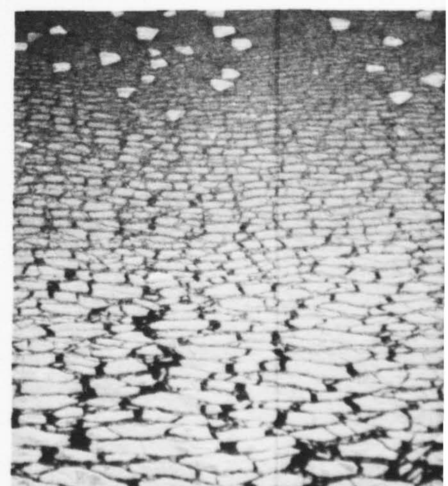
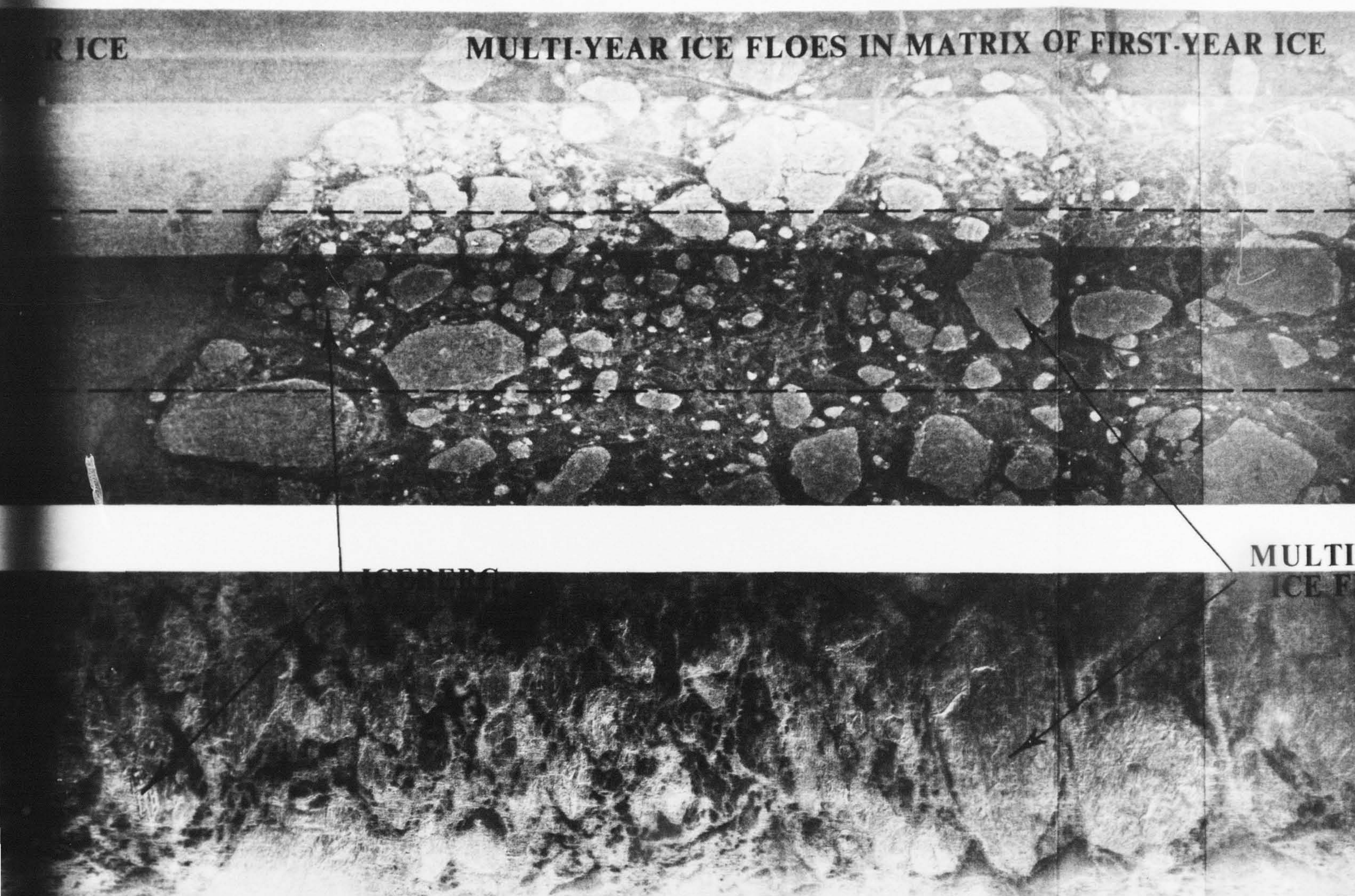
5



A. VIEW ALONG THE NORTH BOUNDARY.

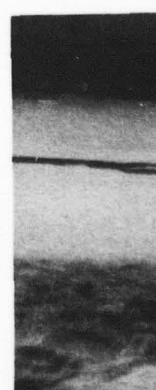


B. WAVE FRACT



URED THIN ICE.

C. BELT OF WAVE FRACTURED ICE AND RAFTED ICE.



D. RA
FR

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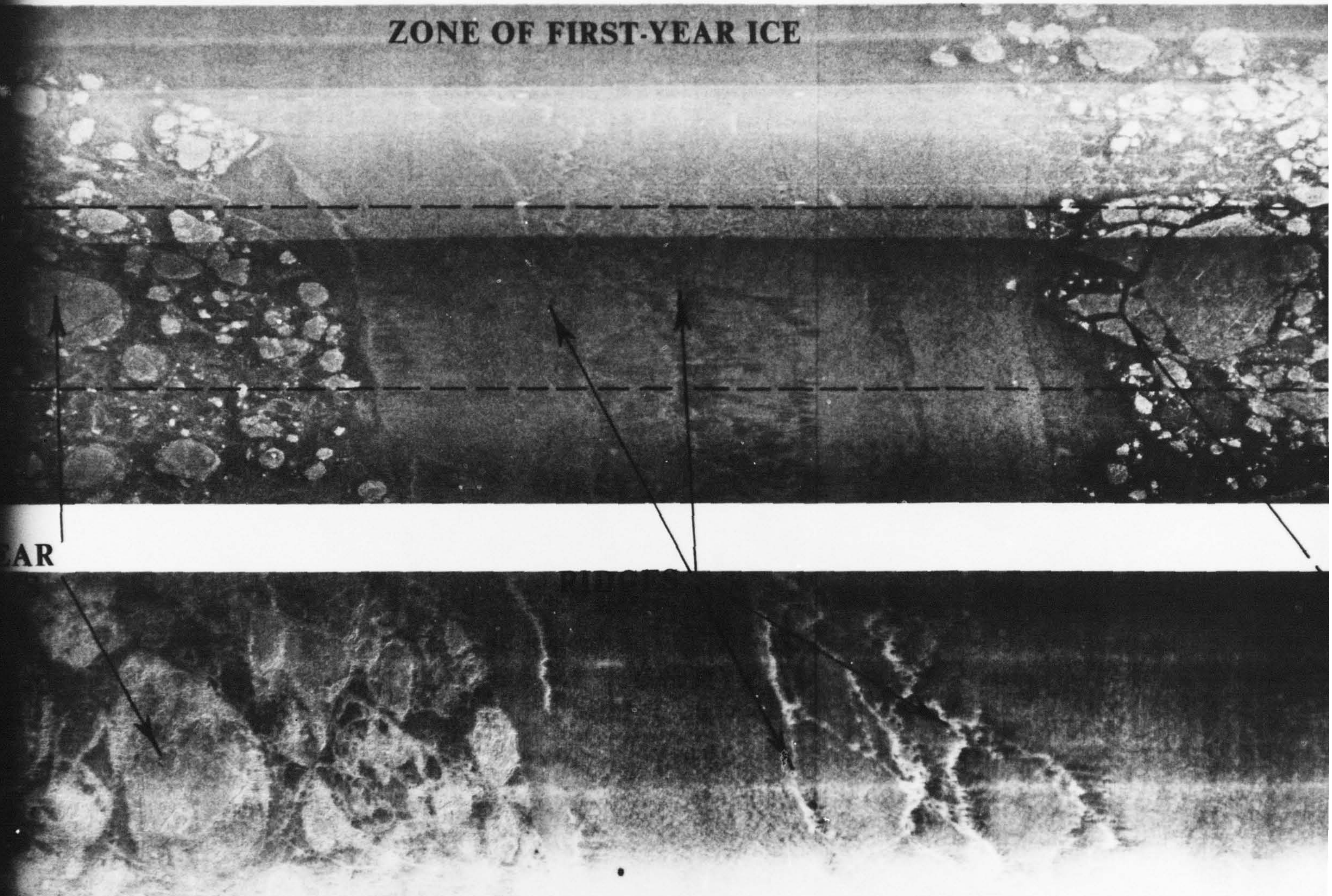


ED ICE WITH BELT OF WAVE
TURED ICE IN THE BACKGROUND.

E. RAFTED ICE SHOWN ADJACENT TO
FIRST- YEAR ICE AT BOUNDARY.

3

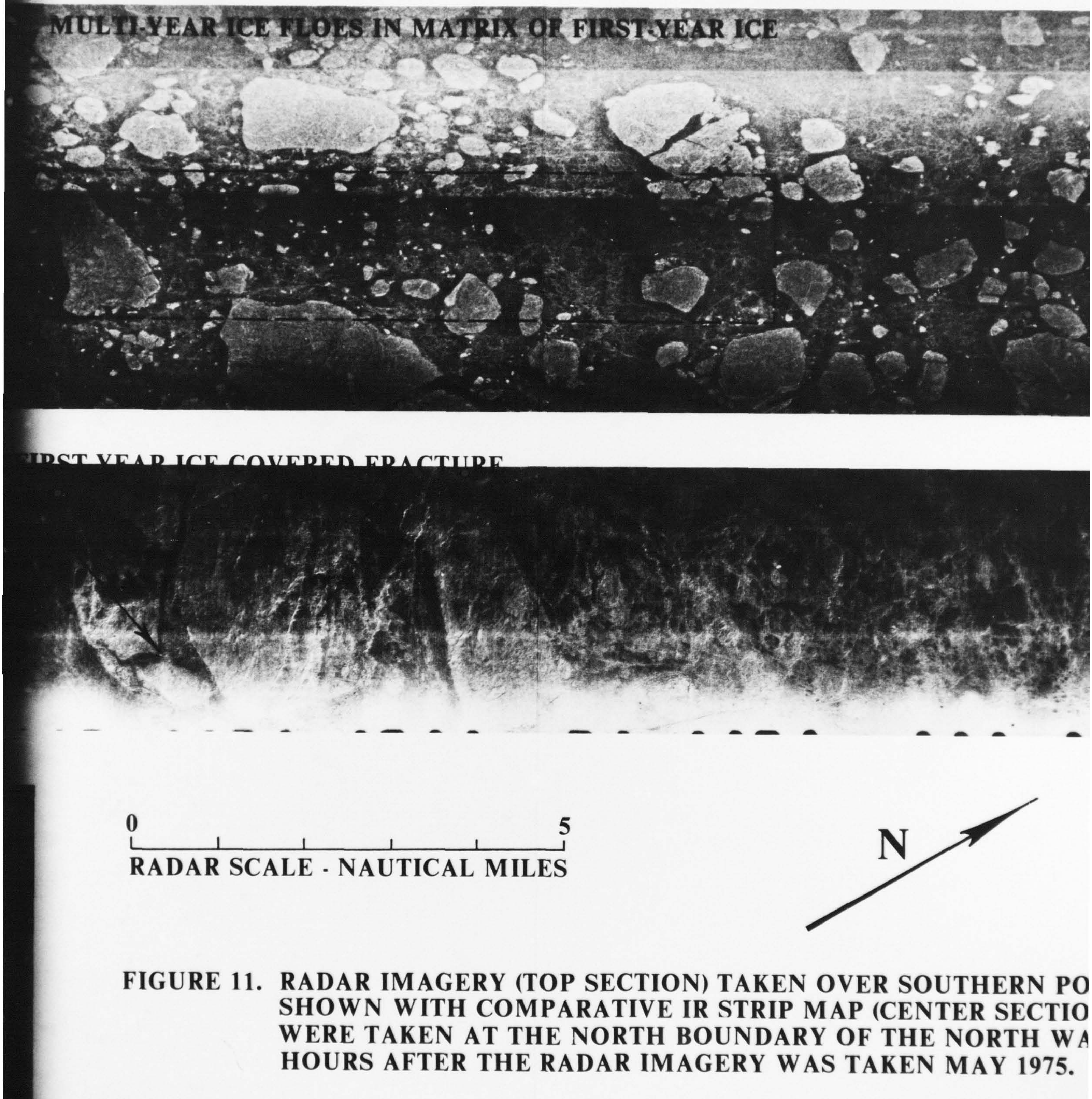
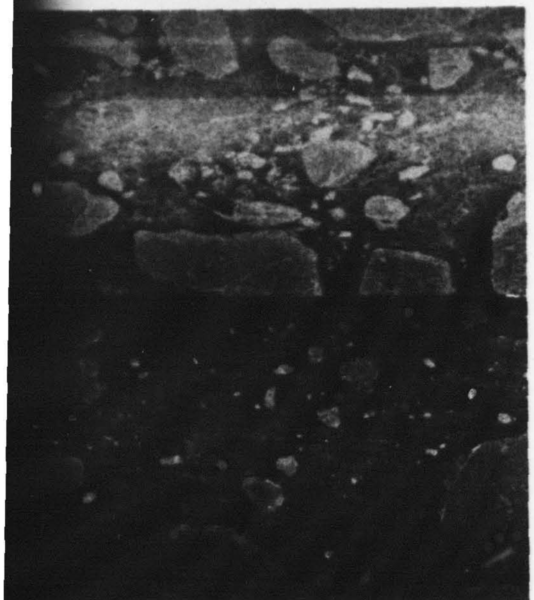
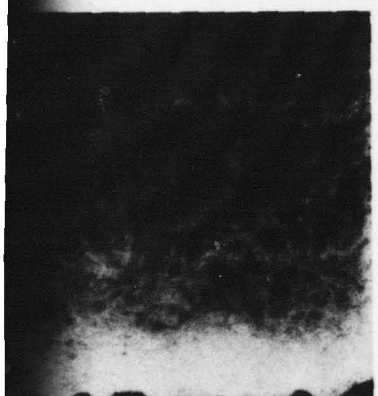


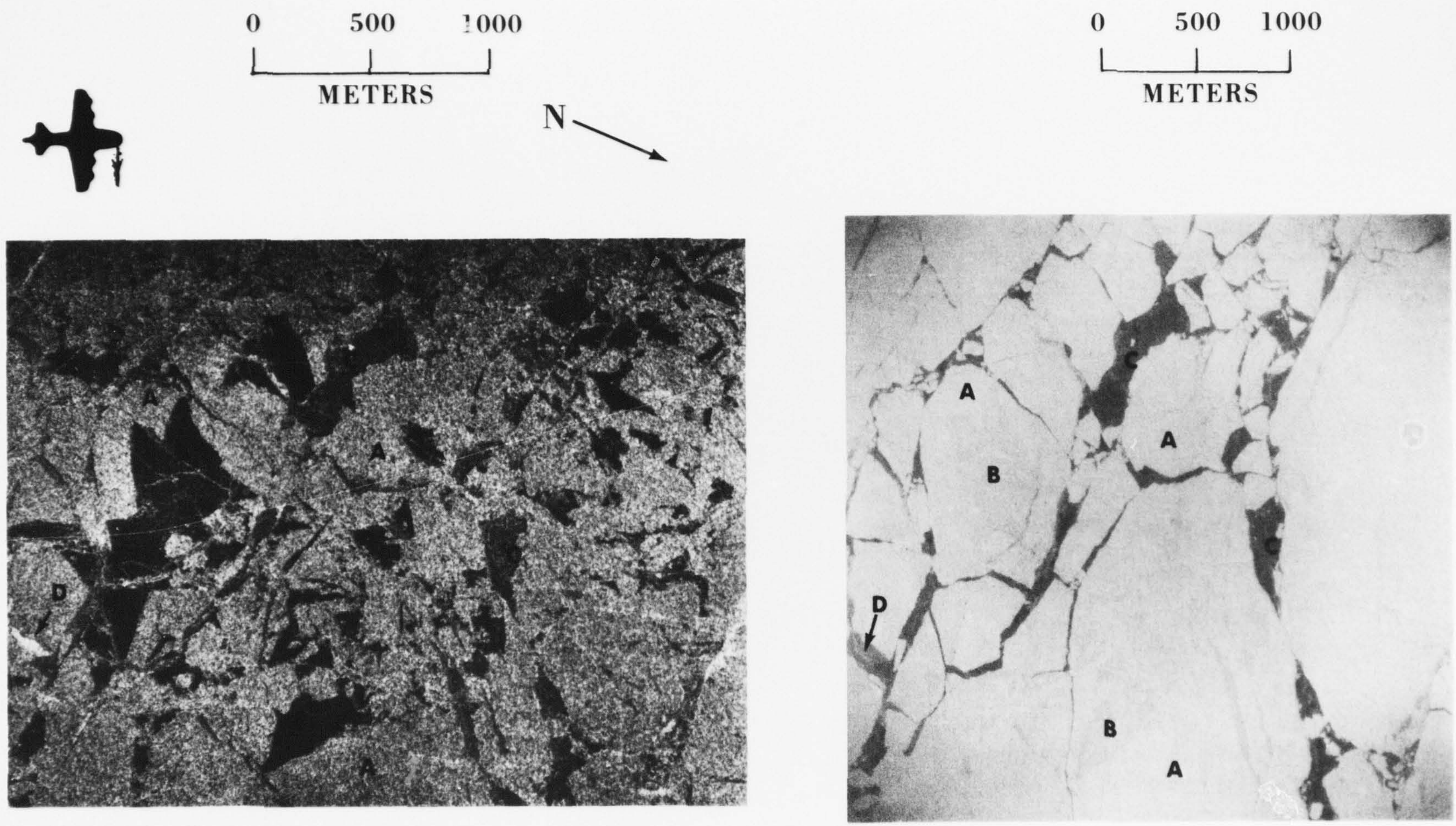
FIGURE 11. RADAR IMAGERY (TOP SECTION) TAKEN OVER SOUTHERN PO
SHOWN WITH COMPARATIVE IR STRIP MAP (CENTER SECTIO
WERE TAKEN AT THE NORTH BOUNDARY OF THE NORTH WA
HOURS AFTER THE RADAR IMAGERY WAS TAKEN MAY 1975.

4





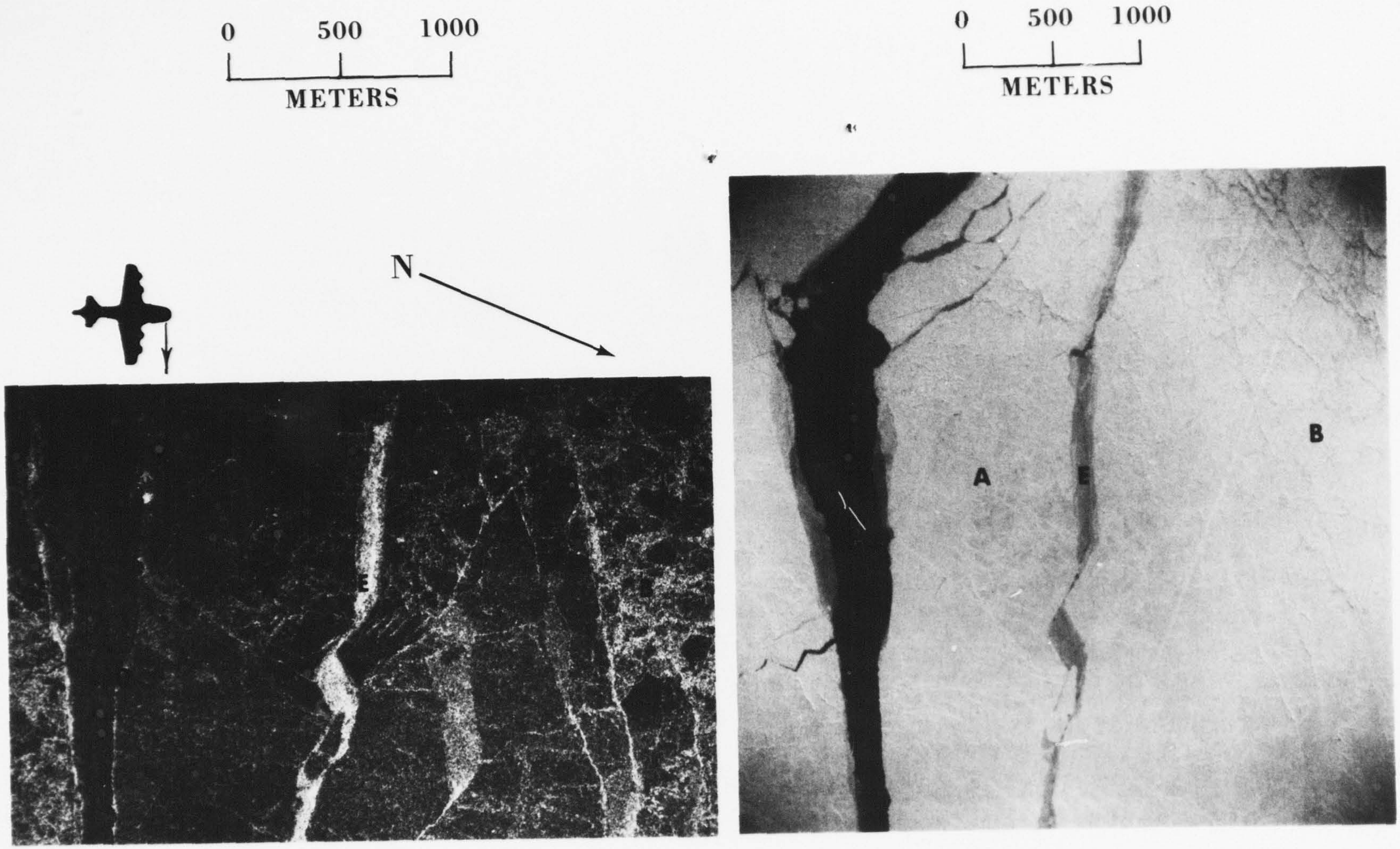
TION OF KANE BASIN
). PHOTOS (BOTTOM)
TER POLYAYA SEVERAL



RADAR

AERIAL PHOTO

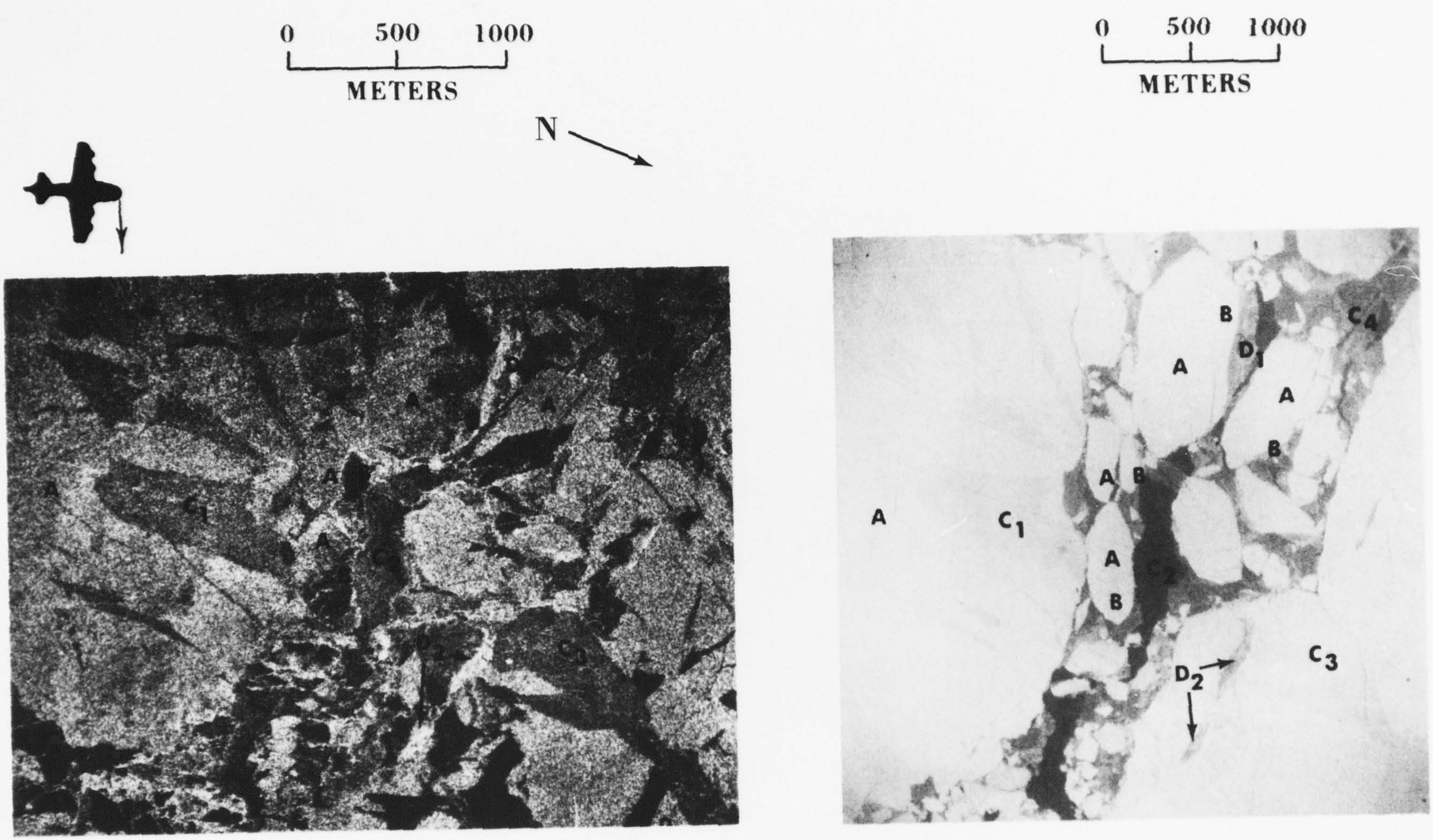
Figure 12. Comparison of Radar Imagery and Aerial Photography — Baffin Bay



RADAR

AERIAL PHOTO

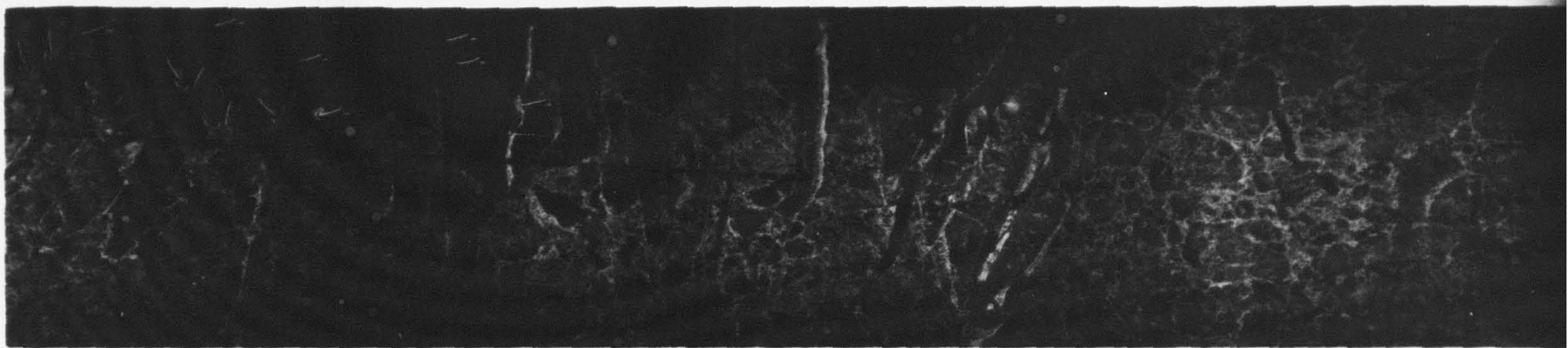
Figure 13. Comparison of Radar Imagery and Aerial Photography — Baffin Bay



RADAR

AERIAL PHOTO

Figure 14. Comparison of Radar Imagery and Aerial Photography – Baffin Bay



1. YOUNG ICE
2. FIRST-YEAR ICE
3. NILAS
4. FIRST-YEAR ICE
5. YOUNG ICE
6. FIRST-YEAR ICE
7. NILAS
8. NILAS
9. MULTI-YEAR ICE
10. OPEN WATER
11. NILAS
12. YOUNG ICE

0
PHOTO

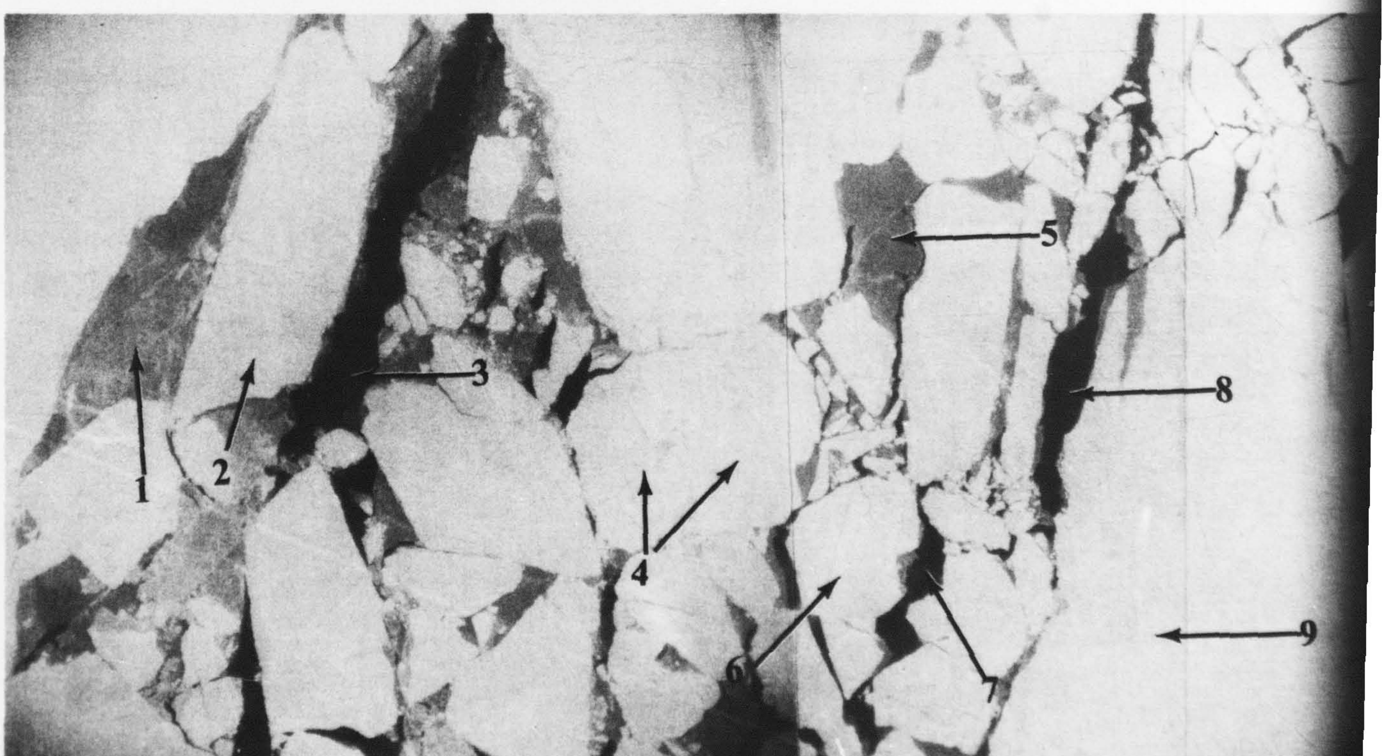


FIGURE 15. RADAR IMAGERY WITH COMPARATIVE PHOTOGRAPHY TAKEN C

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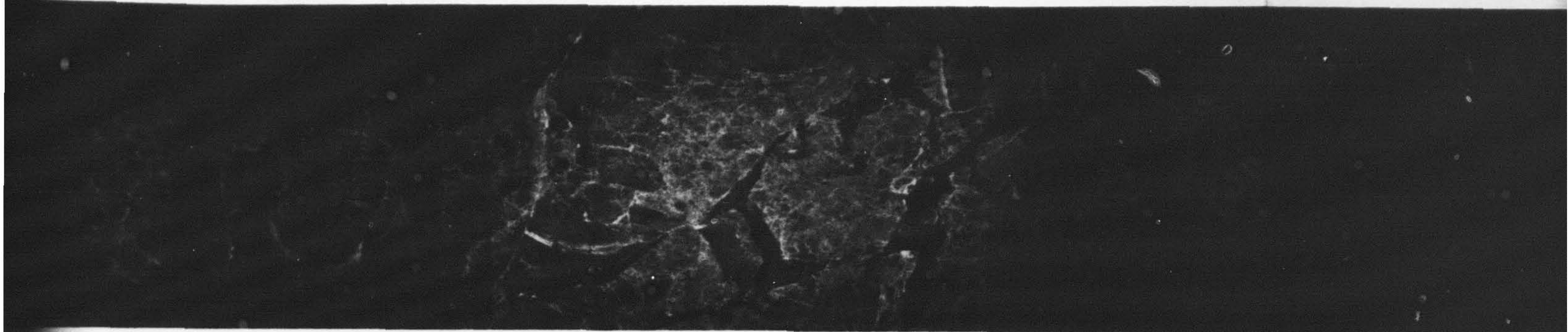
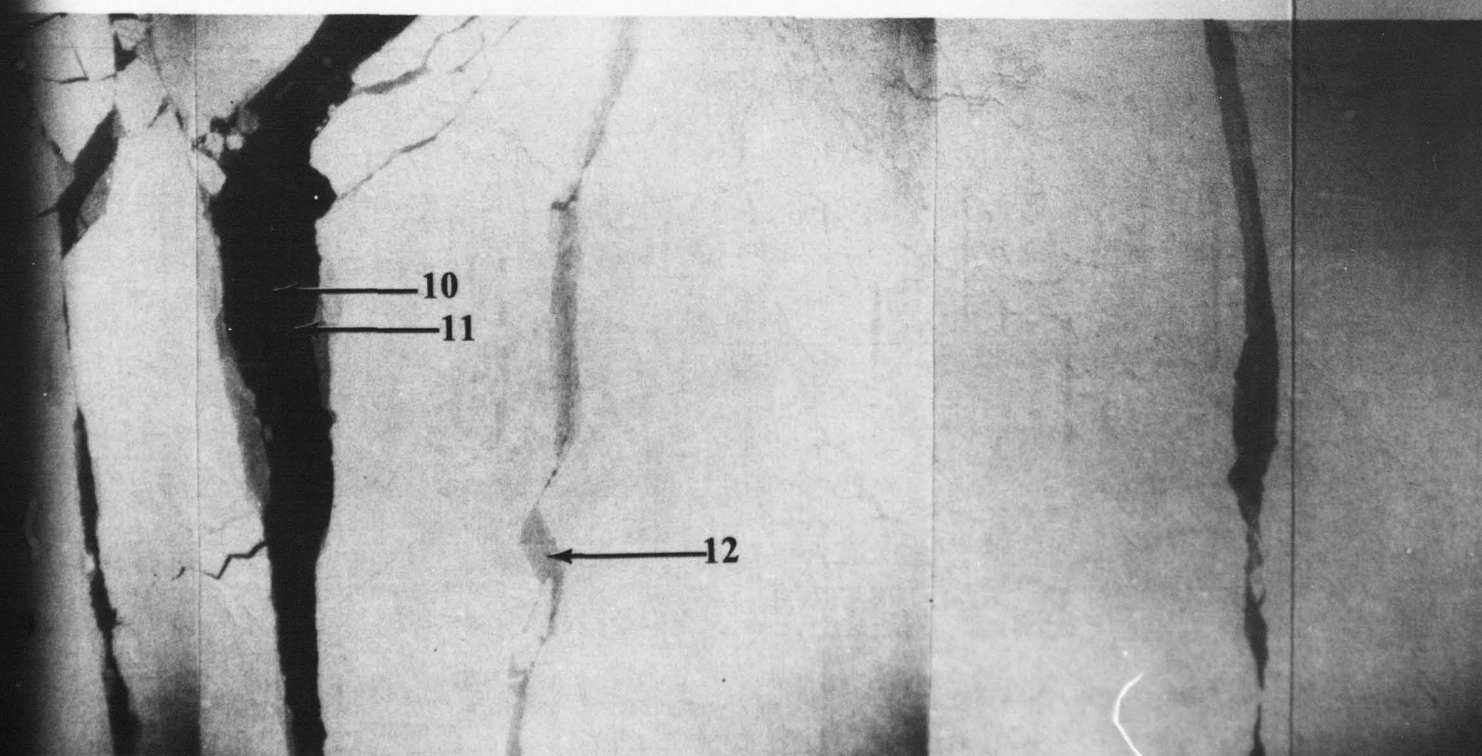


0 500 1000

OTO SCALE (METERS)

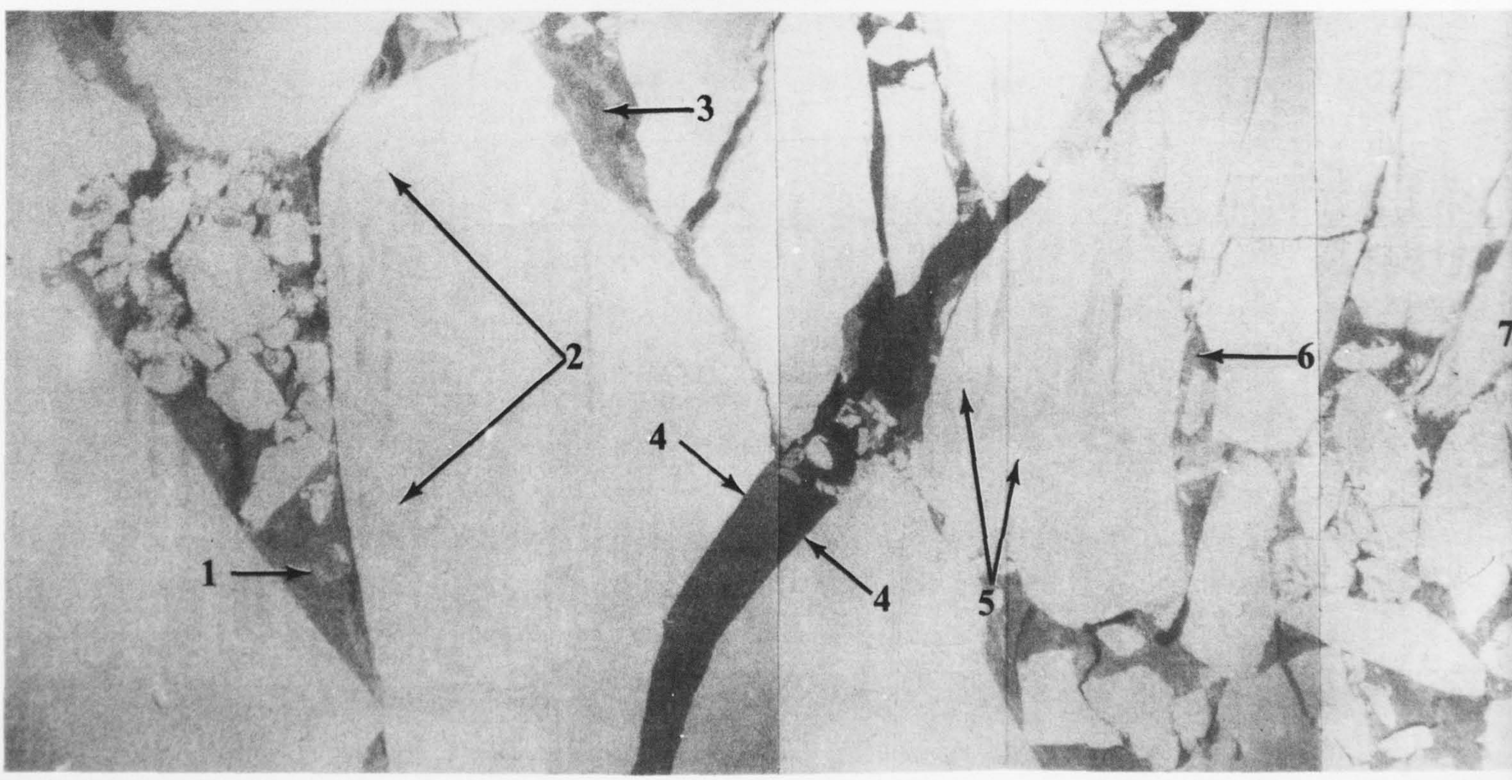
0 5

RADAR SCALE (NAUTICAL MILES)



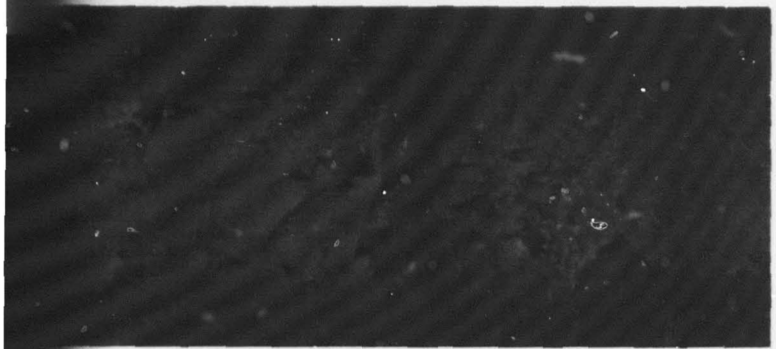
OVER NORTHERN BAFFIN BAY, MAY 1975.

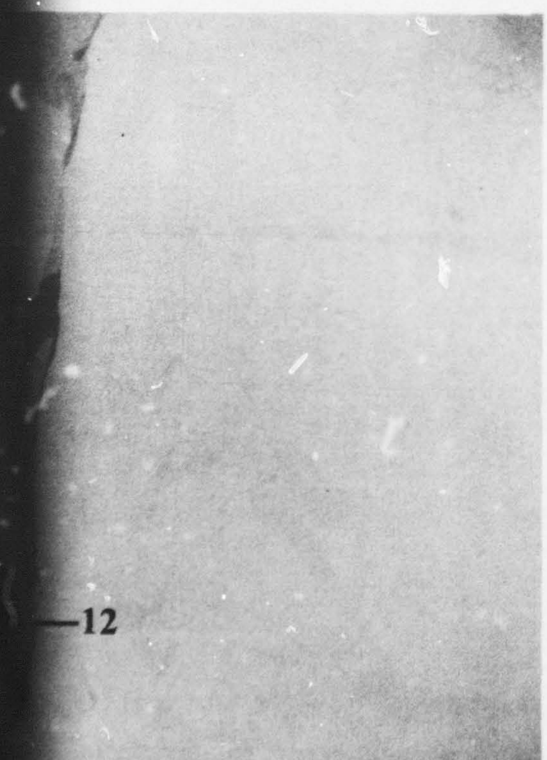
1. YOUNG ICE
2. FIRST-YEAR ICE
3. YOUNG ICE
4. NILAS
5. FIRST-YEAR ICE
6. YOUNG ICE
7. NILAS
8. FIRST-YEAR ICE
9. FIRST-YEAR ICE FLOE
10. YOUNG ICE
11. FIRST-YEAR ICE
12. YOUNG ICE (RAFTED)



3

4





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